FORSCHUNGSBERICHT AGRARTECHNIK

des Fachausschusses Forschung und Lehre der

Max-Eyth-Gesellschaft Agrartechnik im VDI (VDI-MEG) ----

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Development of a decentralized solar assisted milk pasteurizer and improved chiller for rural communities

Dissertation Witzenhausen 2022

Universität Kassel

Fachbereich Ökologische Agrarwissenschaften

Fachgebiet Agrartechnik

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DEVELOPMENT OF A DECENTRALIZED SOLAR ASSISTED MILK PASTEURIZER AND IMPROVED CHILLER FOR RURAL COMMUNITIES

Dissertation zur Erlangung des akademischen Grades Doktor der Agrarwissenschaften (Dr. agr.)

von

M.Sc. Ing. Khawar Saeed Khan

aus Faisalabad, Pakistan

2022

Die vorliegende Arbeit wurde vom Fachbereich Ökologische Agrarwissenschaften, der Universität Kassel als Dissertation zur Erlangung des akademischen Grades "Doktor der Agrarwissenschaften" angenommen.

Tag der mündlichen Prüfung: 14.04.2022

Erster Gutachter : Prof. Dr. Oliver Hensel
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Mündlicher Prüfer: Prof. Dr. Oliver Hensel
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Prof. Dr. Christoph Scherrer
Dr. Martin Wiehle

Gedruckt mit Unterstützung des Deutschen Akademischen Austauschdienstes (DAAD).

Im Selbstverlag: Khawar Saeed Khan

Bezugsquelle: Universität Kassel, FB Ökologische Agrarwissenschaften,
Fachgebiet Agrartechnik,
Nordbahnhofstraße 1a
37213 Witzenhausen

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Witzenhausen den, 24.08.2021 **Khawar Saeed Khan**

Acknowledgements

The journey of my PhD study at the University of Kassel (Witzenhausen campus), Germany started from 1st June, 2015. During the almost four years of research stay in Germany, I have learnt not only academic knowledge, but also on how to become a responsible and independent researcher. I am very grateful that I have worked with and have met many people who have been very helpful and have guided me all the way long. Let me take the opportunity to express my appreciation to all of them.

First of all, I am highly indebted to my supervisor, Prof. Dr. Oliver Hensel, Department of Agricultural Engineering, University of Kassel, Witzenhausen, Germany, for his absolute advice, support and guidance throughout this study. I enjoyed the freedom to explore all options during the various stages of my research. I sincerely honor his vision towards doctoral studies, his philosophy of supervision and the best is his big heart. Even with his busy schedules, he always has time for me whenever I approach his office.

Prof. Hensel has also inspired me in many other aspects of my life; his devotion to work, accomplishments, academic and research excellence, commitment and simplicity are emulative. Without his critical comments and useful suggestions, commitment and rapid feedback, this work would not have been accomplished. Secondly, I am highly thankful to my second supervisor Prof. Dr. Anjum Munir who really helped me conducting this research and provided excellent opportunity regarding the guidance since the start of this project till the end. He was so kind in providing platform for development of machines but also remained highly involved during data collection and optimization process. Without his guidance this work would have not possible to accomplish.

I am grateful to the whole team AGT for all the suggestions and the never-ending support throughout the study period. Further, I will like to thank the anonymous reviewers for their helpful suggestions on the articles presented in this thesis. Without the family-like atmosphere created by the employees of the Agricultural and Bio-systems Engineering Department, this work would not be possible. I am particularly thankful to Christian Schellert, Heiko Tostmann, Karin Link, Michael Hesse, Gardis von Gersdorff, Franz Roman, Waseem Amjad, Faizan Majeed , Zeeshan Munir ,Nabeel Husnain , Aditya Parmar and Sascha Kirchner for their helpful assistance, friendship and hospitality. I gratefully acknowledge the German Academic Exchange Service (DAAD) and ICDD for their financial support of my PhD stipend and appreciate the financial support for my experimental developments. For those who contributed in diverse ways but are denied mention here by my poor memory, and for who did not get the opportunity to contribute, I am still very grateful.

List of publications

The dissertation comprises of the papers already published in peer-reviewed international journals. The list referring to the chapter numbers in the thesis are provided below.

Chapter 3:

Khan, K. S., A. Munir and O. Hensel. 2022. Comparative thermal analyses of solar milk pasteurizers integrated with solar concentrator and evacuated tube collector. Energy Reports. https://doi.org/10.1016/j.egyr.2022.06.001

Chapter 4:

Khan, K. S., W. Amjad, A. Munir and O. Hensel. 2020. Improved solar milk chilling system using variable refrigerant flow technology (VRF). Solar Energy. 197(2020): 317-325. https://doi.org/10.1016/j.solener.2020.01.014

Chapter 5:

Khan, K. S., A. Munir and O. Hensel. 2022. Improving milk value chains: A case study for qualitative-economic feasibility of decentralized solar milk pasteurization and chilling processes. ASABE's Applied Engineering in Agriculture. https://doi.org/10.13031/aea.14805

Conferences and poster presentations

Abstracts submission and posters presented from this research in different international conferences and workshops are as follows:

1. Development of solar assisted milk pasteurizer and mobile chiller unit for rural communities (poster presentation) at ICDD PhD Workshop 2015 Core Concepts of ICDD Research 15–22 April 2015 University of Agriculture Faisalabad (Pakistan) *

2. **Khan, K. S.,** W. Amjad, A. Munir and O. Hensel. Improved solar milk chilling system using variable refrigerant flow technology. ICDD PhD Workshop entitled "Smallholders, Farm Labour, and Collective Agency" Agricultural Faculty, Njoro Campus, 5 - 12 March 2017 University of Egerton (Kenya) (Abstract accepted)

3. Development of solar assisted milk pasteurizer and mobile chiller unit for rural communities (study presented) at ICDD Alumni & PhD Workshop 10 Years ICDD Graduate School: Looking back to look ahead, 12-18 September 2019 University of Kassel, Campus Witzenhausen

**Won best poster award €500 grant from ICDD*

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Nomenclature

Abbreviation	Remarks
EU	European Union
ETC	Evacuated tube collectors
FAO	Food and Agricultural Organization
FHAB	Food Habit and Nutritious
G	Rate of incident solar energy
GHI	Global Horizontal Irradiance
GDP	Gross Domestic Product
HIES	Household Integrated Economic Survey
HTST	High-temperature, short-time
kWh	Kilo watt hour
LTH	Low-temperature-holding
LDCs	Least developed countries
LTH	Low-temperature-holding
MDP	Multi-dimensional poverty
PLSM	Pakistan Social and Living Standards Measurements
PV array	Photovoltaic array
SWH	Solar water heater
SMC	Solar Milk Chiller
SMP	Solar Milk Pasteurizer
SC	Solar concentrator
TR	Tonnes of refrigeration
UNDP	United Nations Development Programme
USA	United States of America
UHT	Ultra-heat-treating
UAF	University of Agriculture Faisalabad
VRF	Variable refrigerant flow
WGET	Single glazed flat plate solar collector
WHO	World health organisation

1 Introduction

The rich quality dairy products provide a great source of essential nutrients in terms of healthy and nourishing food which is demanding worldwide gradually due to overpopulation particularly in developing countries. Milk is the most required and integral constituent of all dairy products, a composite food promising various nutrients required for daily human nourishment regarding nutrients (FAO, 2013). Milk is the most important food attributing to its high nutritional value which contains Water 87.7%, Fat 3.4%, Sugar 4.7%, Protein 3.4% and Ash 0.7% (Reddy et al., 1986; Pandey et al., 2004). The hyperactive bacterial infection initiates at the beginning of milk handling and reaches the maximum level during storage. The acidity increases as the milk get delayed in processing which turns it into a spoiled waste after 5h (Panchal et al.2016; Sur et al,2020). The quality and storage life is enhanced by milk pasteurization and chilling by destroying toxic pathogenic and spoilage microorganisms (Panchal et al. 2017).

In the South Asian region, Pakistan stands at fifth position in the most populous country in the world with its population estimated at 225.8 million in 2021 (World Bank, 2021). The projection by the World Bank released in March 2019 based on the annual population growth rate of 2.4 percent in the latest census, the population is expected to be even higher, at 347 million by 2047. According to FAO (2006a), the share of dairy sector in the national economy is more than that of cash crops (wheat, cotton, and sugarcane). The estimated annual milk production is approximately 42.17 million tonnes, that makes Pakistan one of the world’s highest milk-producing countries (FAO stat, 2010). Around 95% of all milk is produced by small-scale rural and sub-urban holdings (Social Sciences Institute NARC, 2003). There is direct linkage between population growth and demand of dairy products. However, the demand-supply has inverse relation in developing countries where populations has been increasing at faster rate. In underdeveloped countries, around 80% of the total dairy milk is produced by conventional ways without having any access to modern dairy technologies (Kino et al., 2019).

Around 70% of dairy farms operate under smallholder subsistence production systems (with 3 buffalos and 3kg/day yield) known as traditional farms, having lack access to the milk market and produce milk to meet family requirements (International

Center for the Development and Decent Work ICDD, 2013). The annual cow and buffalo milk production in Pakistan approached 38.3 Mt in 2012 (64% from buffaloes) ranking the country 4th globally, after India, USA and China (FAOSTAT,2013). The major milk production is rendered about 80% from rural areas followed by sub urban and urban areas for the rest (Fusions, 2014; ICDD, 2013). Mostly villagers lack access to the milk market and produce milk to meet family requirements carrying an average herd consisting of around three buffaloes, and milk yield per animal is around 3 kg/day (FAO 2011a). Furthermore, around 70% of dairy farms operate under smallholder subsistence production systems (with 3 buffalos and 3kg/day yield) known as traditional farms, having lack access to the milk market and produce milk to meet family requirements (ICDD, 2013). These people need a chilling source close to their farm/milking vicinity for their milk storage to avoid spoilage. For this purpose, a detailed survey was carried out in city district of Faisalabad - Pakistan (31.4278° N, 73.0758° E) within the radius of 25km and area of study for this PhD research that was conducted under the German funded Projects by DAAD and ICDD.

1.1 Current solar energy potential in Pakistan

To meet the energy requirement for the pasteurization and cooling of milk, use of solar energy at milk production sites would be an effective way to maintain the quality of produced milk timely. The solar irradiation is higher in southern parts of Pakistan which decreases towards the northern as shown in Fig.1.1. Faisalabad receives 4.8 kWh/h daily and 1753 kWh/h annually, which makes this city favourable to use solar energy for designing any sort of solar-based decentralized pasteurization and chilling units at farm level. Pakistan has a yearly typical daylight shining ability of around 19 Mega Joules for each square meter, with an ordinary sunshine of 7.6 hours and sun situated radiation of 5-7 kWh/m^2 consistently. The yearly direct run of the solar-based radiation for CSP are estimated to be 7 to 7.5 KWh/m^2/day in most extreme zones of Baluchistan, 5 to 5.5 kWh/m^2/day in Northern Sindh and Southern Punjab and around 4.5 to 5 kWh/m^2/day in the rest of the regions of Pakistan (Shaikh et al., 2012).

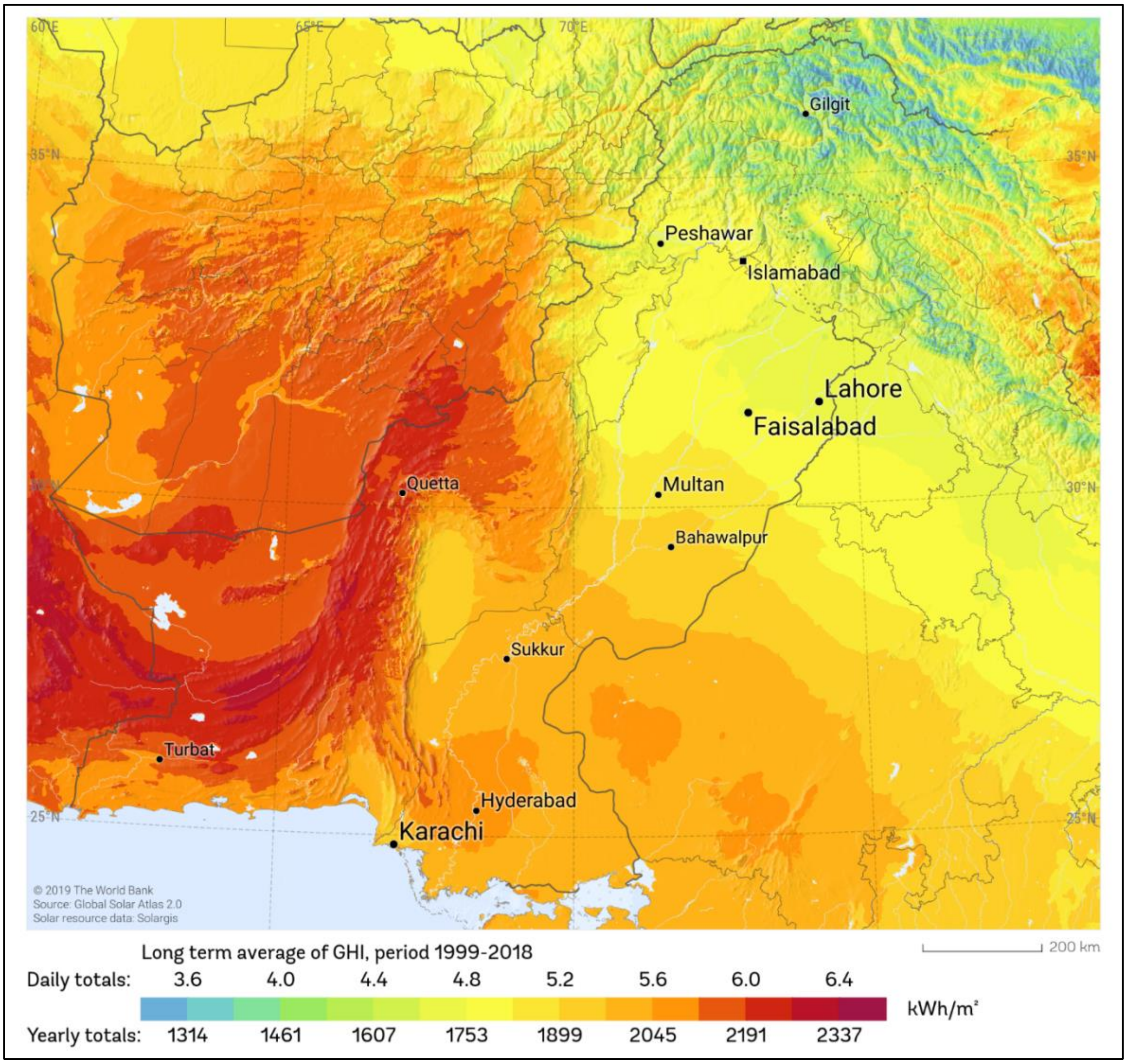

Figure 1.1: Solar Irradiation Potential of Pakistan (source: Global Solar Atlas 2.0)

1.2. Reconnaissance baseline surveys

Keeping in mind the producers (farmers) and consumer’s issues in relation to milk adulteration and quality, two preliminary reconnaissance baseline surveys were conducted within (study area) Faisalabad, Pakistan for milk production and distribution system. Two sets of questionnaires (Annexure C, D) with about 30 questions each were made by keeping in mind all the facts of milk adulteration, distribution problems, storage facilities along with farmers challenges. Interviews were conducted with the consumers and the producers (farmers). Furthermore, the producers were classified into small, middle, and large farmers depending upon the number of animals they have at their farms.

Most of the farmers were poor with a few numbers of animals (cows/buffalos) ranging from 2 to 3 animals per farm. The farmers make quick income by selling small quantities of milk to the middleman on daily basis to sustain their livelihood. However, middle- and high-class farmers who have had significant number of animals were also facing the same issues. Although, their milk production rate was higher as compared to the small farmers but due to the absence of proper milk storage facilities, they were equally affected and compromised by the middleman and milk processing companies. The location coordinates of sampling points are given in Annex A.

The farmer communities had either limited or no access to the electricity due to load management specially in summer (June-August). Moreover, these farmers are unable to afford electricity as the per-unit cost of electricity was much expensive for them. Milking takes place twice a day, the morning milk is sold at a reasonable price, however, the fear of spoilage forces farmers to liquidate his stock at the least offered price. The main reason is the perishable nature of milk which makes the farmers prone to suffer from weather (summer) due to improper post milking facilities at farm level. Eventually, these farmers do not get proper benefits from dairy farming, and it does not become profitable business anymore. Most of the farmers own limited agricultural land for a single-purpose dairy farming where cultivation is not applicable. The market prices of feed and fodder have been significantly increased for the last ten years which made it more difficult to earn money. This results in poor economic conditions of the farming community especially for small and medium scale farmers. Consumers claimed they get poor quality and highly unhygienic milk at a high cost. The middleman makes money by purchasing pure raw milk at the cheapest price, enhances the quantity by adding water or ice to the milk to avoid spoilage because of high environmental temperature due to lack of storage and processing facilities. This leads to further contamination and adulteration as both the water and ice contains bad quality water. Similarly, the farmers claim that they don’t have any other option except liquidation of this milk to the middleman. This results in poor economic conditions of the farming community especially small and medium scale farmers. The baseline survey concluded that more than 70% consumers were ready to pay extra 15-20 rupee per liter of milk if the milk is supplied in processed form.

Therefore, it is important to maintain the milk temperature immediately after milking process. The bacterial reproduction can be minimized in terms of content if raw milk is stored at lower temperature (Sharma et al., 2003). The preheating treatment is inevitable to get the quality milk by killing bacteria as final product to end-user. Heating of milk at precise temperature kills bacteria and harmful microorganisms. Similarly, cooling milk slows down bacterial growth, reducing spoilage and therefore increasing farmer's income, and ensuring safe milk for the consumers. The problem lies at the initial stage of collection and final stage of distribution of retail. Milking takes place twice a day, the morning milk is sold at a reasonable price, however, the fear of spoilage forces farmers to liquidate his stock at the least offered price. The main reason is the perishable nature of milk which makes the farmers prone to suffer from weather (summer) due to improper post milking facilities at farm level. Eventually, these farmers are unable to get proper benefits from dairy farming.

Even though, a significant research work has already been established the role of both technologies Solar Concentrators (SC) and Evacuated Tube Collectors (ETC) for milk pasteurization, however, mostly studies were restricted to local-scale pasteurization using small batch sizes, lacking comparative component-based thermal analyses and unable to address the commercial application to be implemented by the farming community. Moreover, which of the two methods achieves pasteurization promisingly using optimum energy with minimal losses is still questionable. Keeping in view the facts, the present study focusses on the fabrication and widespread thermal analysis of two high-temperature solar applications i.e., SC and ETC for milk pasteurization. The heat energy losses per unit time (W) in terms of optical losses at the aperture areas of both systems were calculated to assess the precise amount of incoming solar energy and distribution losses at the final stage.

All the above-mentioned updated studies were based on a chilling solution within less time, mainly restricted to single compressor type or less battery usage, for preservation of small quantity of milk but lacking the main problem of torque load challenge for solar PV system and selection of an optimally design solar system. The present study investigates the use of refrigerant flow technology to minimize the torque load and by replacing conventional reciprocating compressor by rotary type efficient compressor to make system more energy efficient. Thermal efficient and environmental friendly R410 refrigerant was used in place of conventional type R22 refrigerant in the vapor compression refrigeration system which makes the system more efficient and helps in minimizing the torque load. Milk batch sizes were varied from 50 to 200L and coefficient of performance (COP) were recorded using real time data during the experiments.

The present study enables the development of solar milk pasteurizer (SMP) and solar milk chiller (SMC) pasteurization and energy efficient chiller for the small dairy farmer communities in remote areas of Pakistan. The provision of low-cost milk pasteurizing and the chilling unit will facilitate the small-scale farmers to preserve milk for a longer duration. The study will not only enhance the post milking handling and preservation technologies to overcome rapid spoilage issues specially in summer at the farm level but also to uplift the dairy farming industry in Pakistan. The milk quality assessment after the pasteurization and chilling processes will ensure the quality standards of milk including color, taste and nutrients etc.

1.3 Research hypothesis and research question

The basic research question of the present study based on conducted survey raises as follows

- is it possible to design decentralized SMP and SMC units under the current solar potential to address the farmer and consumer issues by maintaining the proper milk quality?

1.4 Research objectives

1. To conduct a baseline survey regarding the farmer and consumer issues, adulteration in supply chain and available processing/storage facilities at farm level. (**Baseline survey 1.2**).
2. To develop and enable decentralized solar milk pasteurizer integrated with SC and ETC (**Chapter 3**).
3. To develop an improved solar milk chilling system using variable refrigerant flow technology (VRF) (**Chapter 4**).

4. To conduct a comprehensive milk quality analyses and economic feasibility of SMP and SMC. (**Chapter 5**).

1.5 Research methodology

The baseline survey's results highlighted the importance of solar energy utilization for on farm milk processing including pasteurization and chilling for post milking preservation at farm level. The present study was designed to address the above-mentioned issues regarding pasteurization at the farm-scale. Solar-based milk pasteurization enables the decentralized maintenance of milk quality, particularly in remote areas of developing countries. With the introduction of innovative and efficient medium temperature solar technologies, two approaches will be employed to accomplish the pasteurization using solar concentrator (SC) and evacuated tube collectors (ETC). The fresh milk spoils due to increased temperature particularly in suburbs and remote villages. However, using solar PV, minimizing the torque load of cooling machines is a challenging task for the smooth functioning of the milk chilling system especially for the conventional (reciprocating) type of compressors. To overcome this issue, a variable refrigerant flow (VRF) technology will not only solve the torque load issue but also reduce the size of the peak power requirement of the PV array.

1.6 Thesis outline

This doctoral thesis consists of 7 chapters including a few manuscripts published, accepted and under revision status are organized as follows:

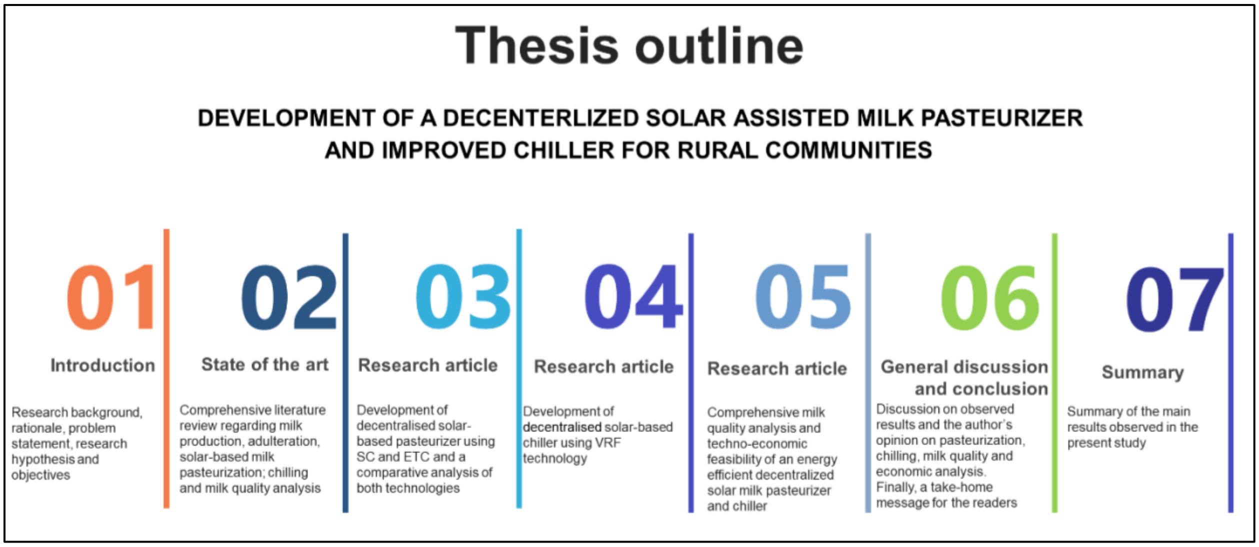

Figure 1.2: Thesis outline and chapters description

❖ **Chapter 1**

Introduction: The introduction chapter gives an insight from the scope of this study including global and regional milk production and solar potential for Pakistan followed by hypothesis and specific objectives of this study.

❖ **Chapter 2**

State of the art: This chapter covers the literature review of the current and previous studies conducted on this topic followed by the significance of this study and challenges faced and the strategies applied to overcome the problems.

❖ **Chapter 3**

Comparative thermal analyses of solar milk pasteurizers integrated with solar concentrator and evacuated tube collector

Solar-based milk pasteurization enables the decentralized maintenance of milk quality, particularly in remote areas of developing countries. With the introduction of innovative and efficient medium temperature solar technologies, two approaches were adopted using solar concentrator (SC) and evacuated tube collectors (ETC).

- **Chapter 4**

Improved solar milk chilling system using variable refrigerant flow technology (VRF)

Based on solar PV system, 2kWp system was used to design and operate a solar-based milk chiller comprising of a milk-chilling tank (200L capacity) coupled with one tonne of refrigeration unit powered by PV panels. A vapor compression refrigeration system was used employing VRF technology to make system more energy efficient by minimizing the torque load.

- **Chapter 5**

Improving milk value chains: A case study for qualitative-economic feasibility of decentralized solar milk pasteurization and chilling processes

This chapter describes the investigation of the milk quality processed with indigenously developed Solar Milk Chiller (SMC) and Solar Milk Pasteurizer (SMP) coupled with an evacuated solar tube collector in comparison with existing milk value chain.

- **Chapter 6**

General discussion and conclusion: This chapter revolves around the discussion of observed results and the author's opinion on solar based technologies including chilling, milk quality and economic analysis. This chapter also revealed concluding remarks, limitations, recommendations and way forward for future research.

- **Chapter 7**

Summary / Zusammenfassung

This chapter summarizes the main results of the present study.

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2. State of the art

Pakistan stands fourth in the list of milk-producing countries worldwide followed by USA, China, and India but a significant amount of raw milk is spoiled due to lack of awareness and processing facilities available in rural areas (Hussain et al., 2014). More than 50% of the rural dairy farms have neither access to electricity nor fossil fuel availability to preserve and process the raw milk effectively. Raw milk undergoes several chemical changes during its transportation to storage/processing sites. In case of Pakistan, about 72 million animals including cows and buffaloes produce about 42 billion liters of milk annually (Shahid et al., 2012) which is normally sold out at low price due to non-availability of post milking facilities at farms level (Tostivint et al., 2016). Raw fresh milk is greatly vulnerable to the spoilage being an excellent growth media for the microorganisms in the tropical region of Pakistan; such milk gets rapidly turns into waste due to the bacterial infection if it is exposed to high temperature for a longer period. The milk quality declines promptly without processes of cooling /heating (FAO, 2000).

2.1. Milk production and distribution in Pakistan

The perishable nature of milk, the long distances between production and consumption sites, inefficient marketing infrastructure, and the number of intermediaries involved in hauling milk through the marketing chain are all factors that can lead to the adulteration or contamination of milk. Lack of hygiene, adulteration by various agents, and absence of a cold chain are the primary contributors to low-quality milk. The dairy industry is highly unregulated in Pakistan, and the marketing chain is exclusively restricted the private sector. In the absence of checks and balances, adulteration is rampant, as each agent in the marketing chain seeks to maximize profits. Due to lack of proper management practices, national-level milk yields are only 1195 liters/lactation for cows and 1800 liters for buffaloes (SMEDA, 2000). To boost production, some farmers use oxytocin injections, which are especially common among market-oriented dairies. Another widespread practice among farmers is the adding of water (often contaminated) to milk to increase its volumes (FAO, 2011). Owing to inadequacy of on-farm processing facilities, the dairy farmers must sell high-quality perishable milk to milkmen and large milk collectors on traditional system (Lateef et al., 2009), thus missing processing incentives ranging from USD 0.0125 to 0.0375/liter (FAO, 2011). About 95% of the milk in Pakistan is marketed raw through informal marketing chains, providing opportunities to unscrupulous persons at every step of milk value chain for adulteration, ultimately resulting in poor quality milk at consumer level (Javaid et al., 2009). Processors often purchase milk based on traditional quality criteria, such as smelling or boiling the milk to detect any curdling or adulteration. Processing operations are often carried out under unhygienic conditions. Costs in the informal milk processing industry depend on the sophistication of operations and the type of products produced. Generally, production costs include manual labor, premises rent, and fuel, ranging from firewood to electricity. For instance, a farm cooling tank of 200L capacity costs USD 3313, and one of 1000L capacity USD 6812, thus, conventionally milk is stored in basic, non-food-grade containers using ice (normally contaminated) inside the containers as a cooling agent to avoid spoiling, especially in the summer season (Awan et al., 2014). In summary, high procurement and operational costs are the main factors which limit the dairy farmers to install chilling units and pasteurizers for on-farm dairy processing. The present study is conducted for improving the existing milk handing system by analyzing the situation through a series of surveys followed by fabricating solar-based pasteurization and chilling system for the milk preservation at farm scale level; this chapter presents the review of literature related to milk production, milk adulteration and pasteurization and chilling systems. The preheating treatment is inevitable to get the quality milk by killing bacteria as final product to end-user. Heating of milk at precise temperature kills bacteria and harmful microorganisms. Similarly, cooling of milk slows down bacterial growth, reducing spoilage and therefore increasing farmer income, and ensuring safe milk for the consumers. Solar energy, not only, provides an extraordinary opportunity to address the decentralized and on-farm processing of milk for value addition but also can provide income generation opportunities in rural community of Pakistan. At the same time, cost of production of processed/pasteurized milk will be far less than the commercial milk production system. The preservation of raw milk for a longer duration would lead to promotion of dairy sector in poor rural community. Dairy sector of Pakistan is an inevitable reality for socio-economic development and the growth of rural economy. Dairying is considered as a secondary source of income after farming for rural communities. It may generate not only the employment and income opportunities next to agriculture, but also promising the supply chain of quality milk products in rural and urban communities as well. Due to increasing awareness on milk quality and standards set by WHO to minimize infant and adult diseases due to poor quality of unprocessed milk, it has become imperative and mandatory to process the milk before selling to the consumers.

2.2. Solar-based milk pasteurization

Pasteurization is an energy intensive unit operation. The thermal treatment of raw milk is highly significant to get final product of good quality and in terms of energy demands of dairy production. Pasteurization is a thermal process in which temperatures lower than 100°C affects the milk and 90–99 % of vegetative forms of microorganisms are eradicated. In developing countries where supply chain has not been developed effectively yet, milk producers have to sell raw milk at low price due to absence of post milking facilities at farm gates. However, a significant amount of raw milk is spoiled due to lack of awareness and decentralized energy efficient processing technology in rural areas. Pakistan produces 42 billion liters of milk annually which covers 11% of total Gross Domestic Product (GDP) of the country (Jassar Farms, 2009); however, the quality control measures are still questionable (Ahmed et al, 2012).

Franco et al. (2008) designed a Fresnel type concentrator based pasteurizing system having a double boiler for goat milk. They removed the automatic tracking device and added a timing device for recording time interval of 40 minutes for the operator. They investigated that goat milk pasteurization must be done within 30 minutes to avoid milk properties lost (taste and color) and delay in cream separation. The goat milk (10L) was pasteurized using steam in an isolated container for about one hour. On achieving the desired temperature, the milk was kept for 30 minutes within a closed container.

Zahira et al. (2009) developed a solar milk pasteurizer (SMP) to assess the probable use of solar energy for milk pasteurization and for the improvement of drinking milk quality in Pakistan. They also observed the microbial inactivation in collected milk samples taken from variety of animals. During the experiment, the temperature was maintained at 65-75°C with an ambient, base and inner space temperature of 40, 85 and 75°C, respectively. They concluded that the pasteurization temperature is easily attainable at low-cost and it may also be used for water pasteurization.

Atia (2010) designed and analyzed a pasteurization system using solar energy as a thermal source for milk pasteurization for remote areas and village communities that lacked electricity and gas. They used a solar flat plate collector to maintain the temperature between 63 and 72˚C within 3-19 minutes in September-November 2009. Their pasteurized milk batch size was restricted to 73.9L (maximum) at 63°C, while 37.3L (minimum) at 72°C. They concluded that solar milk pasteurization is directly proportional to the change in intensity of solar radiation.

Hilphy et al. (2014) designed and tested the efficacy of the solar pasteurizing system in Basrah, Iraq. They used solar collectors as a heat source and documented that solar radiation, absorption rate and the efficiency of collectors are interconnected which increases with an increase in daylight reaches the maximum level at 1:00 pm and starts declining afterwards. The observed average energy of solar radiation in summer and winter is 741 and 673 W/m^2, respectively. Similarly, the rate of efficiency of the solar collector was observed as 40.7%, 46.8%, respectively, and finally, the rate of energy recovered 66.81, 58.53%, respectively. They also observed the rate of productivity 20.20, 13.76 L/h, respectively.

Doborowsky et al., (2015) attained rather a higher temperature (90-91°C), some of employing a tank and evacuated tubes for low-cost solar operated pasteurizer. The main purpose of developing such kind of pasteurizer was to remove the microbiological load in harvested rainwater. They designed a 100L SS storage tank with the dimension of 12m x 1.7m × 0.047m, and borosilicate glass evacuated tubes. The temperature of the pasteurized tank water samples collected ranged from 55 to 57°C, 64 to 66°C, 72 to 74°C, 78 to 81°C and 90 to 91°C. In addition, they recommended that for the pasteurization system, the storage tank could be constructed from an alternative material, other than stainless steel, for large quantity of water.

Atia et al., (2016) carried out an experimental study based on a dual-axis solar tracking device on a solar concentrator for milk pasteurization in Egypt. They used a conventional system comprised of the solar parabolic dish, energy conversion subsystem, and heat exchanger except for the tracking device working in a closed-loop system using light-dependent resistors (LDRs) and operational amplifier (op-amp) chip. They enabled the pasteurization process with a small batch size of 260 ml of milk at 73˚C within 110 seconds, however, hourly production was a bit higher at the rate of 7.5 L/hr. According to their results, the low-cost tracking device tracks solar movement and keep the concentration on a straight axis to the sun. They proposed a 59% and 101˚C increase in cumulative daily heat gain and absorber plate temperature, respectively using this tracking device.

Setiawan et al. (2020) designed a milk pasteurization system using electricity and gas to grab and store the solar thermal energy in water for direct use. The system was composed of an accumulator vessel having an area of 2 x 2 m^2 and a water pipe collector. They observed that it took 12 minutes to increase the water temperature at 82˚C which enables the milk pasteurization (6.75 liters) at 70˚C with 47% efficiency, however, the efficiency could be increased by increasing water volume.

Sur et al., (2020b) designed and developed a solar-based system for milk pasteurization due to the gap between milking and storage in remote areas of India. They developed the setup in Pune, Maharashtra state using stainless-steel (SS304) for storage tank (1.6 x 1.6 x 0.6mm) having a batch size of relatively higher than the previous pasteurization studies i.e. 150 liters. They concluded that the parabolic solar collector (8m^2) performed efficiently at 1:00 pm attaining a temperature of 75°C which was maintained for 30 min for 5Litre/h mass flow rate. The final storage was carried out between 15-20°C in a controlled environment.

Mutasher et al., (2021) designed and developed an economically affordable local solar milk pasteurizer in Suhar city at Sultanate of Oman. They mainly focused on designing parameters of the solar collector and the tilt angle of the collector plate. They observed that the solar collector area of 1.5 x 1 m^2 was needed to attain milk temperature between (63 - 70ºC) within half an hour. They further added that the tilled angle of 27˚ performs much better than 4˚.

The single glazed flat plate solar collector and water in glass evacuated tube solar water heater (WGET-SWH) are mostly used. The WGET-SWH is considered as the most prevalent technique to take advantage of solar energy (Liu et al., 2013). Being a promising technique, the evacuated tube thermal collector (ETC) is a more recent development compared to the conventional flat plate collector. Its high-performance, reliability and commercial application in cold climate makes it popular as compared to conventional technologies (Liu et al., 2017). To process more quantity of milk in reasonable time, limited use of solar concentrators has also been reported.

To assess the design and efficiency of a pasteurization process employing solar energy through any of above-mentioned technologies, a detailed thermal analysis is of much importance. Various researcher conducted thermal analyses for dairy processing industry but none of these was about a pasteurization process integrated with both evacuated tube collector and solar concentrator (Scheffler reflector) separately. Srinivasan et al. (2018) exhaustively covered the evaporation and drying activities in a milk processing industry and determined that the exergy efficiencies of many thermodynamic units were reported below 20%. Yildrin and Genc (2017) executed a detailed energy and exergy analysis of dairy food powder production system. Moreover, pasteurizers having diverse designs can provide diverse results of thermal analysis using same product. Thus, the key objective of a thermal analysis for an improved or a newly developed process is to find out energy distributions and optimum operating conditions to save energy for effective milk pasteurization. Some of the recent studies particularly discussed optical losses in terms of shadowing and blocking of solar radiations (Balghouthi and Qoaider, 2017). Some authors improved thermal efficiency of solar pump while others addressed energy/exergy analyses and thermal modelling of ETC. Even though, a significant research work has already been established the role of both technologies for pasteurization, however, mostly studies were restricted to local-scale pasteurization using small batch sizes, lacking comparative component-based thermal analyses and unable to address the commercial application to be implemented by the farming community. Moreover, which of the two method achieves pasteurization promisingly using optimum energy with minimal losses is still questionable.

2.3. Solar-based milk chilling

Raw milk is considered as a tremendous medium for contagious growth of bacteria and other pathogens which soon get accelerate when stored at ambient temperature. Therefore, it is necessary to maintain the temperature soon after the completion of milking process. The bacterial reproduction can be minimized in terms of content if it is stored at lower temperature (Sharma et al., 2003). The preheating treatment is inevitable to get the quality milk by killing bacteria as final product to end-user. Heating of milk at precise temperature kills bacteria and harmful microorganisms. Similarly, cooling milk slows down bacterial growth, reducing spoilage and therefore increasing farmer income, and ensuring safe milk for the consumers. In many remote localities, one of the underlying reasons for not receiving life-saving vaccines is the lack of electricity to store the vaccines in the required refrigerated conditions. Solar Photovoltaic (PV) refrigerators have been considered as a viable and green solution to store the vaccines in remote localities having no access to electricity (Uddin et al., 2021).

Wayua et al. (2013) designed and tested a low-cost charcoal evaporative cooler to store camel milk in an arid pastoral area of northern Kenya. They maintained the temperature inside the cooler as lower as 1-11°C lower than the outside temperature and inside humidity was 0-49% higher than outside. They successfully achieved and maintained an average temperature drop of 10.5±0.4°C much lower than ambient temperature (29-32°C) during extreme hot hours of the day (14:00 hours). The reduction rate was observed as 35.6% and statistically significant ($p \leq 0.05$). They also observed that the cooling efficiency varies between 74.2 to 86.7% in a day.

Torres-Toledo et al. (2015) presented a calculative method to estimate the transient performance of a small on-farm milk cooling system for PV applications in Stuttgart, Germany. Two units of a commercial DC refrigerator operate at −10°C and at 4°C for ice production and milk preservation, respectively. The development of milk temperature and energy consumption during a cooling event was studied experimentally at different ambient temperatures of 20°C, 30°C and 40°C. They observed ambient temperature between 20°C and 40°C having a COP reduction of around 30% and a total daily energy consumption increase of around 100%. The specific total energy consumption of the system per litre milk was between 30 Wh/L and 58 Wh/L for the studied ambient temperature range. They suggested that the model could be used for the optimization of photovoltaic stand-alone systems at specific locations.

Gabrielli et al., (2016) presented a performance and economic-based comparison of solar cooling configurations using a new integrated approach combining the hourly thermal-optical performance assessment of the solar systems with the economic aspects. ETC with single effect Lithiumbromid (LiBr) absorption chiller and compact solar linear concentrating Fresnel collectors with single effect or medium temperature double effect LiBr absorption chiller were used. They concluded that compact solar linear concentrating Fresnel collectors with single effect or medium temperature double effect LiBr absorption performed much better than ETC considering that all the produced cold thermal energy could be delivered to a final user. They further added that this system configuration showed the possibility to adapt the Levelized Cost of Cooling (LCOC) comparable with standard electric compression cooling. However, technology improvements and economies of scale were necessary to reduce solar field costs in the range of 150-250 €/m2.

Sur et al. (2020) considered a cooling system for residential and utility buildings in both South and North Europe and investigated the most promising alternatives when solar energy was to be used to supply the cooling demand of these buildings while the heat rejection temperatures were high. Both the solar electric and solar thermal routes are considered. It is concluded that presently vapour compression cycles in combination with PV collectors lead to the economically most attractive solutions. The second-best option was vapors compression cycles driven by electricity delivered by parabolic dish collectors and Stirling engines. The best thermally driven solution was the double-effect absorption cycle equipped with concentrating trough collectors closely followed by desiccant systems equipped with flat-plate solar collectors. Adsorption systems options were significantly more expensive.

Sur et al., (2020b) designed and developed a solar-based milk chilling system for milk to fill the gap between milking and storage in remote areas of India. They developed the setup in Pune, Maharashtra state using stainless-steel (SS304) for storage tank

(1.6*1.6*0.6) having a batch size of relatively higher than previous chilling studies i.e. 150 liters. They carried out the experimental setup for attaining the milk chilling at 15–20°C for 10–12 h using a flat plate collector having area of 8 m^2. The experimental result shows that for 400 L/h hot water supplied at 90°C (desorbed-bed temperature at 80°C), 35°C condenser temperature and evaporator temperature 5°C system's specific cooling power varies between 5.7 kW/kg to 5.4 kW/kg (variation due to uncertainty analysis).

Uddin et al., (2021) carried out the performance evaluation of a solar PV powered vaccine refrigerator based on hourly cooling load calculations and refrigeration cycle simulations for remote locations in Bangladesh. They focused on performance parameters for three environment-friendly refrigerants: R152a, R1234yf, and R1234ze(E) compared against the commonly used R134a for two remote, off-grid locations in Bangladesh and South Sudan. They concluded that R152a outperformed the remaining two higher Coefficients of Performance (COP) (2%−5.29%) throughout the year. Techno-economic analysis showed an energy system providing electricity to the refrigerator with R152a also had a lower Levelized cost of electricity (0.48%− 2.54%) than the systems having other refrigerants in these locations.

2.4. Innovation and significance of solar milk pasteurizer

Keeping in view the facts, the present study focusses on the fabrication and widespread thermal analysis of two high-temperature solar applications (SC and ETC) for milk pasteurization. The heat energy losses per unit time (W) in terms of optical losses at the aperture areas of both systems were calculated to assess the precise amount of incoming solar energy and distribution losses at the final stage.

2.5. Innovation and significance of Solar Milk Chiller

All the above-mentioned updated studies were based on a chilling solution within less time, mainly restricted to single compressor type or less battery usage, for preservation of small quantity of milk but lacking the main problem of torque load challenge for solar PV system and selection of an optimally design solar system. The present study investigates the use of refrigerant flow technology to minimize the torque load and the conventional compressor (reciprocating) replaced by rotary type to make system more energy efficient. This not only provides the solution for chilling only but also enables the selection of a best compressor based on minimum torque load employing variable refrigerant technology for 50 to 200L of milk batch sizes with high COP using real time data recorded during experiments.

2.6. Milk quality analysis

The simplest and oldest form of adulterant in milk is water to increase the volume for profitable commodity (Bhatt et al., 2008), but contaminated water has a potential risk to human health regarding waterborne diseases (Campos Motta et al., 2014). When water is added to milk, its foamy appearance diminishes. To give milk its foamy appearance, artificial detergents are commonly added (Lateef et al., 2009). Middlemen usually attempt to counter the dilution by adding cane sugar to extend the solid content of the milk. They also add additives like starch to mask the effect of dilution by water and to increase the viscosity of milk up to the consumer acceptance level (Afzal et al., 2011). For whiteness and genuine appearance, potassium and calcium salts of thioglycolic acids can also be added (Soomro et al., 2014). Milk is also adulterated illegitimately with formaldehyde, melamine, urea, and sugars for preservation, protein content enhancement, and taste improvement, respectively (Ahmad et al., 2016). On the other hand, microbial contamination of pasteurized milk can occur from different sources, such as dirty milking equipment, inefficient pasteurization, contamination from the environment, poor packaging, unsatisfactory sanitation, and unsuitable storage temperature or a combination of these (Fulya, 2011). Milk is transported to peri-urban and urban areas at ambient temperature from far-off places distancing up to 100 km, thus contaminated bacteria might get multiplied and attain a high number during this transportation. These high counts are linked with unhygienic milk handling, contamination from animal bedding, mixing of normal milk with the milk collected from the animal suffering from streptococcus uberis induced mastitis, etc. (Muhammad et al., 2009).

Owing to inadequacy of on-farm processing facilities, the dairy farmers have to sell high-quality perishable milk to milkmen and large milk collectors on traditional system (Lateef et al., 2009), thus missing processing incentives ranging from USD 0.0125 to 0.0375/liter (FAO, 2011). About 95% of the milk in Pakistan is marketed raw through informal marketing chains, providing opportunities to unscrupulous persons at every step of milk value chain for adulteration, ultimately resulting in poor quality milk at consumer level (Javaid et al., 2009). Processors often purchase milk based on traditional quality criteria, such as smelling or boiling the milk to detect any curdling or adulteration. Processing operations are often carried out under unhygienic conditions. Costs in the informal milk processing industry depend on the sophistication of operations and the type of products produced. Generally, production costs include manual labor, premises rent, and fuel, ranging from fuel wood to electricity. For instance, a farm cooling tank of 200L capacity costs USD 3313, and one of 1000L capacity USD 6812, thus, conventionally milk is stored in basic, non-food-grade containers using ice (may be contaminated) as refrigerant to avoid spoiling, especially in the summer season (Awan et al., 2014). In summary, high procurement and operational costs are the main factors which limit the dairy farmers to install chilling units and pasteurizers for on-farm dairy processing.

To meet the energy requirement for the cooling of milk, use of renewable energy at farm scale level would be an effective way to maintain the quality of produced milk in a timely manner. The study will enhance the post milking handling and preservation technologies to overcome rapid spoilage issues specially in summer at the farm level and hence not only to improve poor farmer community living standards but to elevate the dairy farming industry in Pakistan. The milk quality assessment will ensure the color and taste preservation after getting completed the pasteurization and chilling process.

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3. Comparative thermal analyses of solar milk pasteurizers integrated with solar concentrator and evacuated tube collector

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3.1 Abstract

Solar-based milk pasteurization enables decentralized maintenance of milk in remote areas of developing countries like Pakistan. Two innovative and efficient medium temperature range solar techniques; solar concentrator (SC) and evacuated tube collectors (ETC) were employed and compared based on theoretical and experimental analyses for an expedient and effective milk pasteurization. The detailed thermal analyses of both techniques were conducted to investigate the useful energy and losses during pasteurization. The available energy was estimated to be 8.11 and 5.63 kWh at the aperture areas of SC, ETC, respectively. Theoretically, it was also evident that SC, ETC require 4.68 and 4.22 kWh, respectively for a temperature difference of 35-40°C during pasteurization for the designed milk batch size. However, under practical conditions, heat energy consumed for the milk pasteurization system coupled with SC, ETC was recoded to be 3.56 kWh and 3.91 kWh respectively; this value lies from 3.78 – 4.32 kWh to pasteurize 100-liters of milk for a temperature difference of 35-40°C. The predicted value of efficiency for SC, ETC was found to be 57.71 and 74.88 % respectively. The efficiency values under field conditions for SC, ETC were found to be 54 and 71.41% respectively. Generally, both systems performed exceptionally however, ETC outperforms SC theoretically and practically attributing to significantly reduced optical and thermal losses. This study concluded that ETC is efficient, simpler in design, stable, compact and cost-effective which provides an excellent opportunity for decentralized milk pasteurization.

Keywords: solar milk pasteurization; evacuated tube collector; Parabolidal concentrator; steam receiver; thermal analyses; Milk processing at off grid locations.

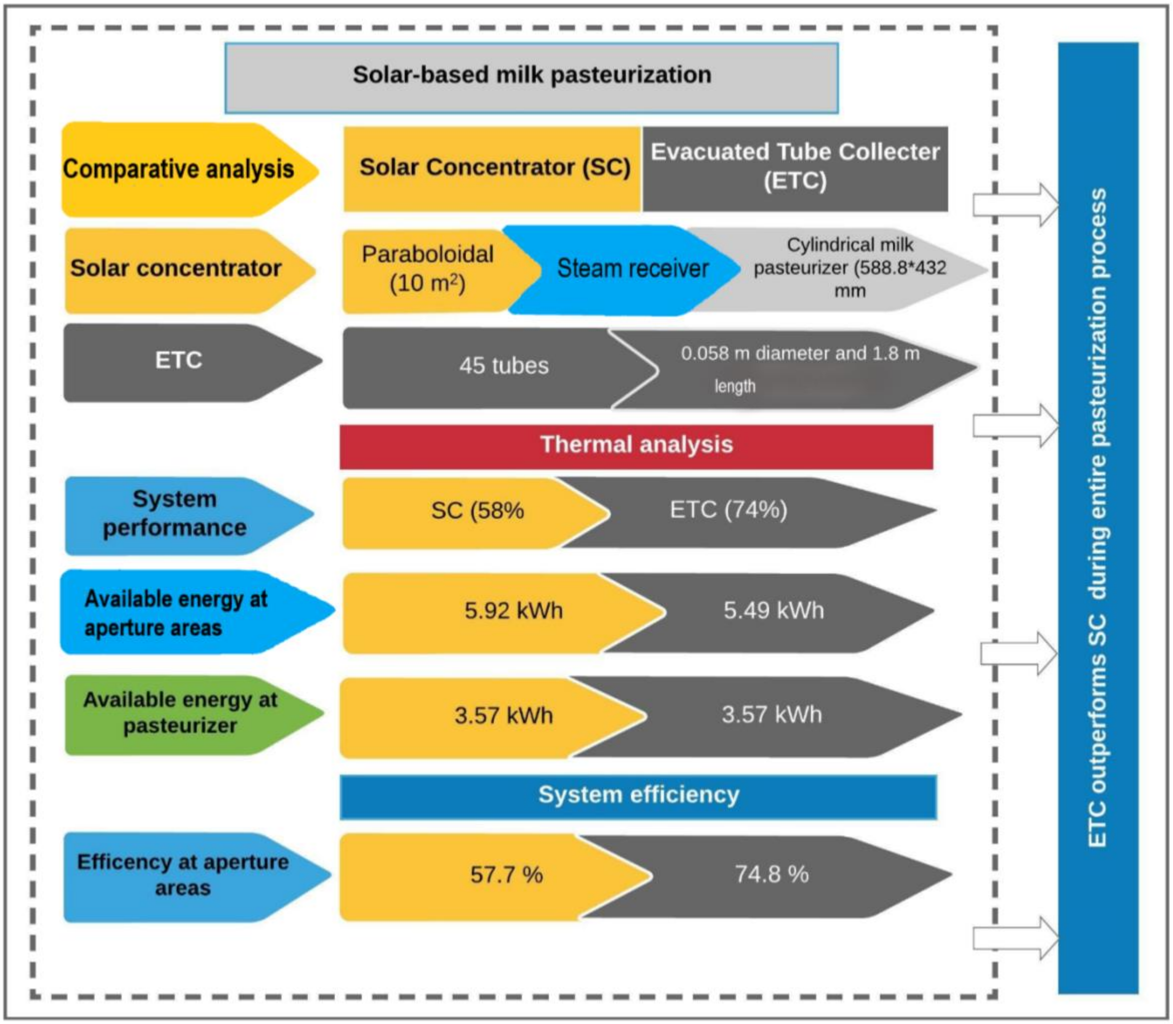

Figure 3.1: Graphical abstract

3.2 Introduction

Pasteurization is an energy intensive unit operation. The thermal treatment of raw milk is highly significant to get final product of good quality and in terms of energy demands of dairy production. Pasteurization is a thermal process in which temperatures lower than 100°C affect the milk and 90–99 % of vegetative forms of microorganisms are eradicated. In developing countries where supply chain has not been developed effectively yet, milk producers have to sell raw milk at low price due to absence of post milking facilities at farm gates. Pakistan stands fourth in the list of milk producing countries in the world after United States of America (USA), China and India (Hussain et al., 2014) however, a significant amount of raw milk is spoiled due to lack of awareness and decentralized energy efficient processing technology in rural areas. Pakistan produces 42 billion liters of milk annually which covers 11% of total Gross Domestic Product (GDP) of the country (Jassar Farms, 2009) however the quality control measures are still questionable (Ahmed et al, 2012).

The milk pasteurization is carried out using four ways depending upon the temperature and duration of pasteurization for low-temperature-holding (LTH), high-temperature, short-time (HTST)as well as ultra-heat-treating (UHT) along with batch pasteurization. LTH pasteurization refers to the heating of milk up-to 63ºC for 30 minutes within an insulated tank where steam enters into the tank from an outer source. Whereas, for high-temperature, short-time (HTST) pasteurization, hot water rises the milk temperature at 72 °C for about 15 seconds. The milk flows under a defined pressure between metallic plates and between pipelines but heat applied at the outer periphery. In ultra-heat-treating (UHT) pasteurization, the milk heated until 140 °C within 4 seconds by spraying milk into a chamber containing the high-temp steam under defined pressure. After the heating process, it cooled down suddenly in the vacuum chamber later packed in a pre-sterilized sealed food grade material container. Batch type pasteurization is the common and classic technique for milk pasteurization. For this process, milk is heated until 63 °C (145.4°F) in absence of air and light in a closed container for half an hour at the same temperature. The present study focuses on on-farm milk pasteurization possibilities using LTH for small-scale farmers and entrepreneurs. The pasteurization using HTST and UHT is discouraged for local unskilled farmers due to complexities in as high-pressure vessels with dedicated mountings and other accessories which are highly expensive. This LTH is equally good and operates under the WHO standers for pasteurization of milk. Additionally, it provides the solution to couple the system with efficient solar thermal technologies (SC, ETC) to make a decentralized low-cost solar dairy farm for value addition and income generation at local-scale farm level in developing countries.

In order to make milk pasteurization an energy efficient process and to provide on-farm pasteurization facility, use of solar energy not only provides an extensive energy resource to address the decentralized and on-farm processing of milk for value addition but also can provide income generation opportunities in rural community of developing nations. Therefore, use of solar energy at milk production sites would be an effective way to maintain the quality of produced milk timely. Panchal et al (2017) presented a comparative review of solar based pasteurization. The reported studies were conducted in various regions of the world using different technologies such as solar evacuated tube collector (ETC) and solar flat plat collector milk pasteurization as shown in Table 3.1.

Table 3.1: Comparative review of previous studies regarding solar based milk pasteurization using SC and ETC

Authors	Heating source	Research development
Wayua et al., 2012	Solar panels	Design and performance analysis of milk pasteurizer
Neilson and Person et al.,2016	Solar panels	Design of solar panels for milk pasteurization
Franco et al., 2016	SC	Designed an economical tracker-less concentrator
Balghouthi and Qoaide., 2017	SC	Optical, losses: in terms of shadowing and blocking
Tiburcio et al., 2018	SC	Improved solar pumped laser efficiency

Liu et al. 2013,2017	ETC	Economic analysis and design using machine learning algorithm
Mishra et al., 2015	ETC	Thermal modelling of ETC
Daghigh and Shafieian, 2016	ETC	Theoretical and experimental analysis of ETC
Ersoz., 2016	ETC	Energy and exergy analysis of ETC
Khan et al., 2020	SC	Design and performance analysis of milk chiller
Sur et al., 2020	SC	Design and development of a solar-based system for milk pasteurization
Mutasher et al., 2021	SC	Designed parameters of the solar collector and the tilt angle of the collector plate

Use of flat plate collector for pasteurization (Zahira et al., 2009; Atia, 2010; Wayua et al., 2013) discussed remarkable results dealing with small quantity of raw product (milk). In order to get rather a higher temperature, some of them designed a system employing a tank and evacuated tubes for low cost solar operated milk pasteurizer (Doborowsky et al., 2015). Passive solar water heaters are widely used usually for low-medium ranged thermal applications (Panchal et al. 2019). The single glazed flat plate solar collector and water in glass evacuated tube solar water heater (WGET-SWH) are mostly used. The WGET-SWH is considered as the most prevalent technique to take advantage of solar energy (Liu et al., 2013). Being a promising technique, the evacuated tube thermal collector (ETC) is a more recent development compared to the conventional flat plate collector. Its high-performance, reliability and commercial application in cold climate makes it popular as compared to conventional technologies (Liu et al., 2017). In order to process more quantity of milk in reasonable time, limited use of solar concentrators have also been reported. Franco et al. (2008) designed a Fresnel type concentrator based pasteurizing system. The goat milk (10 liter) was cooked using steam in an isolated container in about 1 hour. Atia et al. (2016) conducted an experimental study to equip a solar concentrator with dual axis sun tracking device for milk pasteurization. The thermal system was comprised a solar parabolic dish, energy conversion sub-system, and heat exchanger. The system was able to pasteurize about 260 ml of milk at 73˚C in average time 110 seconds. The average hourly productivity of solar pasteurized milk was about 7.5 liters.

In order to assess the design and efficiency of a pasteurization process employing solar energy through any of above-mentioned technologies, a detailed thermal analysis is of much importance. Various researcher conducted thermal analyses for dairy processing industry but none of these was about a pasteurization process integrated with both evacuated tube collector and solar concentrator (Scheffler reflector) separately. Singh et al. (2018) performed a thermal analysis of a dairy food processing plant. The overall energy efficiency and efficiency pertaining to executable potential of energy in UHT Milk Processing Unit were reported to be 86.36 % and 53.02 %. Srinivasan et al. (2018) exhaustively covered the evaporation and drying activities in a milk processing industry and determined that the exergy efficiencies of many thermodynamic units were reported below 20 %. Yildrin and Genc (2017) executed a detailed energy and exergy analysis of dairy food powder production system. Moreover, pasteurizers having diverse designs can provide diverse results of thermal analysis using same product. Thus, the key objective of a thermal analysis for an improved or a newly developed process is to find out energy distributions and optimum operating conditions to save energy for effective milk pasteurization. Some studies particularly discussed optical losses in terms of shadowing and blocking of solar radiations (Balghouthi and Qoaider, 2017). Some authors improved thermal efficiency of solar pump while others addressed energy/exergy analyses and thermal modelling of ETC. Similarly, Sur et al., (2020) designed and developed a solar-based system for milk pasteurization due to the gap between milking and storage in remote areas of India. They developed the setup in Pune, Maharashtra state using stainless-steel (SS304) for storage tank (1.6 x 1.6 x 0.6 mm) having a batch size of relatively higher than the previous pasteurization studies i.e. 150 liters. They concluded that the parabolic solar collector (8m2) performed efficiently at 1:00 pm attaining a temperature of 75°C which was maintained for 30 min for 5Litre/h mass flow rate. The final storage was carried out between 15-20°C in a controlled environment.

Mutasher et al., (2021) designed and developed an economically affordable local solar milk pasteurizer in Suhar city at Sultanate of Oman. They mainly focused on designing parameters of the solar collector and the tilt angle of the collector plate. They observed that the solar collector area of 1.5 x 1 m2 was needed to attain milk temperature between (63 - 70ºC) within half an hour. They further added that the tilled angle of 27°C performs much better than 4°C.

However, all the developed techniques were restricted to pasteurize a small milk batch size of 5L using $1m^2$ collector area, such techniques could have been used on a small domestic scale. However, for a commercial scale where batch size matters, no viable solution using minimum energy and losses is still available. To achieve a commercial-scale pasteurization (100-200L) of milk batch, the collector area needs to be increased which not only requires multiple resources (high initial cost, capital) but a precise engineering design to use maximum available power with least losses at various exposed parts of collectors to sunlight.

Although, significant research work has already been established on the role of both technologies for pasteurization, however, most studies were restricted to local-scale pasteurization using small batch sizes, lacking comparative component-based thermal analyses and unable to address the commercial application to be implemented by the farming community. The small-scale batch sizes do not apply to the local farming communities; therefore, the present study enabled the design of a 200L batch size using both SC and ETC. The storage of the pasteurized milk was a major problem for the small farmers, this issue was resolved by a previously designed chilling unit (Khan et al, 2020). The quality analysis of pasteurized milk using SC, ETC and payback period for these units has been discussed in (Khan et al, 2022). The development of such units has already addressed the quality and economic analysis in a viable manner for long-term milk storage. However, which of the two methods achieves pasteurization promisingly using optimum energy with minimal losses is still questionable. For the present study, the precise design with commercial-scale pasteurization (200L) milk batch size was fabricated in terms of a 10m2 collectors' area and 24 tubes of ETC. Such a large area for the collector and a large number of ETC have never been designed so far to achieve efficient pasteurization with minimum losses at all parts. Keeping in view the aforementioned facts, the present study focusses on a widespread comparative thermal analysis of two high-temperature solar applications (SC and ETC) for milk pasteurization. Detailed thermal analyses have been conducted for each combination for comparative assessment of energy distribution and design for the effective use of solar energy in dairy sector. The entire system was divided into segments that were evaluated based on energy flow and results were compared. The study provides a detailed procedure to conduct a comparative thermal analysis of a pasteurization process integrated with two different heating sources.

3.3 Material and Methods

This study aimed at the development and thermal analyses of solar assisted milk pasteurizers coupled with a SC compared with an ETC based system. Both the systems have been developed at Solar Park, University of Agriculture Faisalabad – Pakistan (31.44° N, 73.13° E)**.** Complete methodology adopted for pasteurization and thermal analyses was shown in Fig. 3.2.

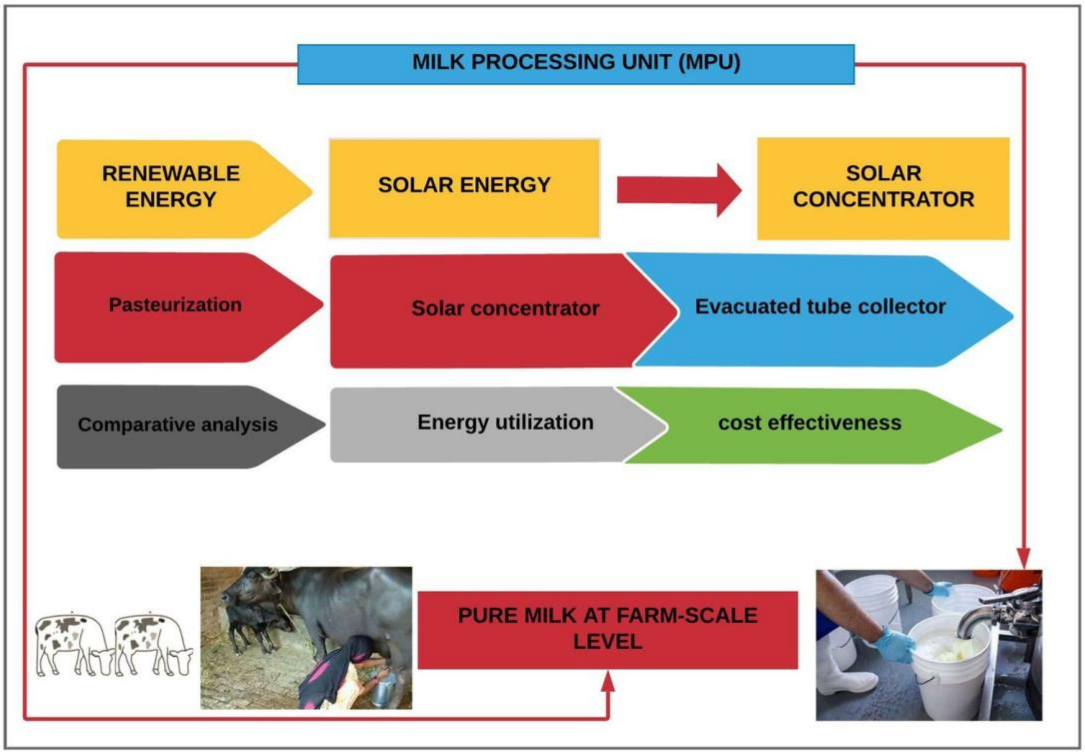

Figure 3.2: Methodology flow chart for the comparative analysis of solar concentrator and evacuated tube collector

3.3.1 Solar milk pasteurization using solar concentrator

Decentralized applications particularly in humid regions enable the milk pasteurization system. The pasteurization process is generally designed conveniently to facilitate various milk batch volume during experimental setup. The process of pasteurization was carried out using Low Temperature Holding (LTH) method. During this process, the milk is placed in a pasteurizer tank and heated by passing steam or hot water in the outer insulated pipes wrapped around the pasteurizer tank. The milk is heated up to a temperature of 63°C which is maintained essentially at this temperature at least for 30 minutes duration. The pasteurizer tank is equipped with an agitator for supplying uniform heat to every milk molecule. Finally, the milk temperature is immediately dropped to a temperature not greater than 4°C for storage purpose. Various kinds of solar concentrators can be used for milk pasteurization but some of versatile parabolidal solar connectors (e.g., Scheffler fixed focus concentrators) provide fixed focus on the ground surface without mounting the receiver as a part of the solar concentrator; thus, making various food processing applications possible as per approved standards operating procedures. It also provides very simple and automatic daily and seasonal tracking which automatically reflects the solar radiation at the targeted focus. The solar milk pasteurization system comprises a Scheffler fixed focus concentrator, steam receiver and a milk pasteurizer. The complete solar system was fabricated in the workshop of Energy Systems Engineering, University of Agriculture, Faisalabad. Prior to construction, a jig was fabricated for 10 m^2 Scheffler reflector for precision and accuracy to make the desired part of solar concentrator. The solar system comprises a 10 m^2 surface area paraboloidal concentrator which was fixed in standing position facing towards south and its axis of rotation is inclined at an angle of 31.25° (latitude of the site) with the horizontal. The daily tracking system was used to rotate the reflector along the polar axis which triggers according to solar direction.

3.3.2. Solar milk pasteurization using Evacuated Tube Collector

There are different options to couple various types of solar collectors but evacuated tube collector (ETC) was chosen because of its high efficiency, compactness and durability and it does not need any tracking system; ETC with built-in heat pipes were selected to pasteurize the milk. The glass vacuum tubes material was borosilicate glass and structure were concentric dual tube geometer. The outer and inner diameters of tubes were Ø58mm ± 0.7mm and Ø47mm ± 0.7mm respectively. The glass tube length was 1800mm ± 5mm and vacuum was $P<5x10^{-3}$ Pa. The average heat loss coefficient from tubes was 0.8W/m^2 °C. For the storage of hot water stainless steel tanks with 200-liter storage capacity were installed. The temperature from ETC can be achieved up to 100+ °C. Fig. 3 shows the schematic layout for the heating of water used for pasteurization using vacuum tube collector.

The ETC area can be calculated using following formula

$$\boldsymbol{A} = \frac{\boldsymbol{m}.\boldsymbol{C_p}.\Delta\boldsymbol{T}}{\boldsymbol{I_t}.\boldsymbol{\tau}.\boldsymbol{\alpha}.\boldsymbol{t}.\boldsymbol{\eta_{th}}} \quad (3.1)$$

Where, 'A' is the area of receiver tube exposed to radiation (m^2); 'm' is the mass of water (kg); 'C_p' is specific heat capacity of milk to be pasteurized ($kJkg^{-1}K^{-1}$); 'ΔT' is the change in temperature of the milk in pasteurizer (K), I_t is the intensity of total solar radiation solar radiation (W/m^{-2});'τ' is transmission coefficient of ETC outer glass tubes, 'α' is absorption coefficient of ETC inner absorber tubes and 't' is the time in seconds, 'η_{th}' is the thermal efficiency of the complete solar milk pasteurization system. This includes all the thermal losses from ETC, storage tank, milk pasteurizer and all connected pipe lines from where heat energy is transferred.

As this study is focused on the calculation of heat energy required to increase the temperature milk (m = 100 kg, Specific heat: 3.89 $kJkg^{-1}K^{-1}$) for a temperature rise of 40°C in one hour and a half time (t =5400 s) for a tropical region like Faisalabad (N 31° 25' 46.8048", E 73° 4' 14.3112") lying in solar belt having average GHI as 800 kWm^{-2} (I_t = 0.8 kWm^{-2}). Evacuated tube collectors have high values of transmission and absorption coefficient (τ = 0.95; α=0.95). The thermal efficiency was calculated to be 0.85 for the system.

Substituting these values in Eq. (1), the area required is calculated to be 4.695 m^2 respectively. Aperture area of one tube is calculated by multiplying diameter (0.058 m) of the absorber tube with its length (1.8 m) and calculated to be 0.1044 m^2 and the number of tubes is calculated by dividing total absorber area by the absorber area of one tube and calculated to be 44.97 and 45 identical tubes were used for the milk pasteurization to process the milk under the aforementioned resources of the system.

Hot water from the storage tank is circuited to the outer side of the pasteurizer with the help of a square pipe in the spiral form for effective heat transfer to the milk filled inside the tank. However, the tank material is of food grade SS-304 as per standards of milk pasteurization. The outer shell of the pasteurizer is insulated with poly urethane. A mechanical stirrer having 60 rpm is installed to distribute heat equally, required for a good pasteurization. It also helps to drop down the milk temperature rapidly to proceed for the chilling process. A temperature above 100°C can be easily achieved within Global Horizontal Irradiance (GHI) of 600-800 Wm^{-2}.

3.3.3 Combined Pasteurizer tanks

A 100-liter combined cylindrical milk pasteurizer tank for both heating sources was fabricated of stainless-steel material (SS 304; Food Grade) having diameter and length as 558.8 mm and 432 mm, respectively as shown in Fig. 3. An electric motor with stirrer was installed at the top of pasteurizer unit to stirrer milk continuously operated at variable speed. A helix coil made of square pipe (25.4 mm x 25.4 mm) was installed at outside of the inner tank for thermal heat transfer. The hot water which was heated up to 90 to 100ºC through heat source is passed through the helix stainless steel coil to raise the temperature of milk to make it bacteria free during pasteurization process. The hot water was entered inside the helix coil from the top side of inlet pipe and drained from the lower end of the helix pipe for counter current heat transfer application. A centrifugal electric pump was used with three different operating speeds to flow the water inside helix pipe for maintaining optimum milk pasteurization process. Hot water energy was added to the milk to pasteurize it. Second milk pasteurizer tank was also developed having the same dimensions but there is no helix coil but instead only jacket was utilized for steam utilization from steam receiver produced with the help of a SC. Both the pasteurizers are insulated with 50 mm glass wool insulation to minimize thermal losses.

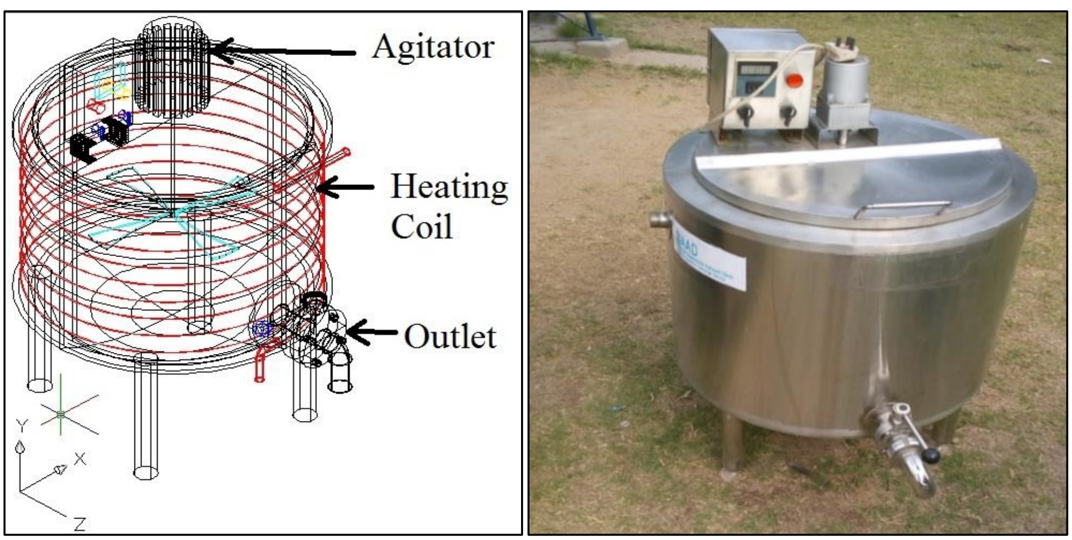

Figure 3.3: CAD and developed milk pasteurizer tank

3.3.4 Parameters of the Existing Prototype of the Milk Pasteurizer

The milk pasteurizer is composed of four major sections attributed to the geometry and heat application distribution. The parameters of the existing prototype are shown in Table 3.2.

Table 3.2: Metadata for the current prototype of solar milk pasteurizer

Parameters	Receiver Top	Receiver Lateral	Receiver bottom	Pasteurizer Bottom	Pasteurizer Lateral
Vessel section	Top	Lateral	Bottom	Bottom	Lateral
Geometric shape	Circular	Cylindrical	Circular	Circular	Cylindrical
Length (m)	-	0.10	-	-	0.432
Diameter (m)	0.40	0.40	0.40	0.5588	0.5588
Thickness (m)	0.01	0.01	0.01	0.002	0.002
λ-tank (W/m°C)	15	15	15	15	15
Insulation	-	0.10	0.10	0.050	0.050
λ-insl (W/m°C)	-	0.40	0.40	0.40	0.40
λ-gi(W/m°C)	-	0.40	0.40	0.40	0.40
ε-material	0.94	0.25	0.25	0.25	0.25
ε-gi	-	0.35	0.35	0.35	0.35

3.3.5 Available energy and losses in a solar milk pasteurization coupled with solar concentrator

Telescopic clamps were used on either ends of the SC (top and bottom) to account for seasonal tracking which is done manually at half the solar declination angle which automatically induces the desired shape required for summer and winter solstice positions. Glass mirrors (specific reflectance > 0.90) were used on the reflector (consisted of a centre bar and seven crossbars as well as of aluminium profiles) to form the required lateral part of a paraboloid. The main advantage of Scheffler fixed focus concentrator is that it provides fixed focus near to ground with the changing position of sun with respect to earth throughout the day and hence its utilization from small cooking to industrial configurations is possible; nevertheless, there is great compromise on the reduction of available aperture area to reflect the radiation at targeted focus on fixed place on ground.

Solar radiation after reflecting from the SC are absorbed by the aluminium steam receiver. Solar mat was applied on top side of the steam receiver to behave like a black body to absorb solar radiation reflected from SC. Steam is produced as a result of concentrated radiation at receiver and this steam is used to pasteurize the milk.

With the help of steam jacket surrounded around the milk pasteurizer, the condensate thus produced is again recycled to produce water again thus utilizing the latent heat of vaporization of water for quick rise in temperature of milk. The pasteurization unit is cylindrical in shape (diameter = 0.516 m x 456 m) having total capacity of 100 Liters. The schematic of solar milk pasteurization using solar concentrator is given in. 3.4.

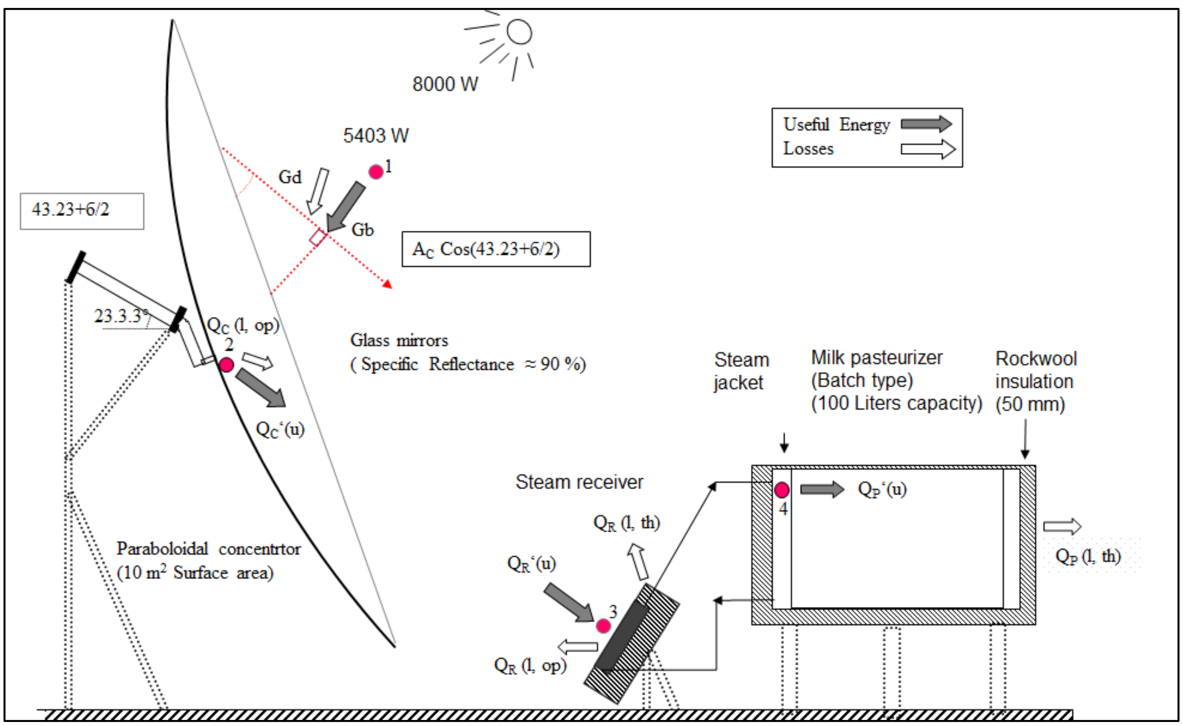

Figure 3.4: Explanation of available energy and losses in a solar milk pasteurization coupled with SC

After the construction and development process, complete energy balance of the solar milk pasteurization system was carried out by considering the useful energy available and losses at different sections of the system. This study can be used to develop any size of solar milk pasteurization system. The black and white arrows in Fig.3.4 represent useful energy available and losses at four main points (1-4) of the system.

3.3.6 Available Solar Power at Paraboloidal Concentrator

Though Scheffler concentrators provide fixed focus at ground level, yet there is a big compromise on aperture area as a certain angle has to be maintained in order to reflect the beam radiation at targeted focus. The Scheffler design maintains this angle at (43.23 ± α/2) with the angle of incident beam radiation and thus aperture area becomes relatively smaller. So, actual input energy is calculated by multiplying this fraction of area with intensity of beam radiation. The pyranometer is mounted on the reflector in the line of beam radiation by mounting a black pipe so that it can only record beam radiation. Total energy available on SC (Q_p) is given by the following relation

$$Q_c^{'} = G_b \, A_s \cos\left(43.23 + \frac{\alpha}{2}\right) \quad (3.2)$$

and

$$A_a = A_s \cos\left(43.23 \pm \frac{\alpha}{2}\right) \quad (3.3)$$

Where, A_s is the total surface area of Scheffler, A_a is the aperture area of paraboloidal concentrator during any day of the year and α is the solar declination;

Solar declination is calculated by using the following equation

$$\alpha = (180/\pi)[0.006918 - 0.399912\,cos\,(n-1)2\pi/365 + 0.070257\,sin(n-1)]2\pi/365$$
$$-0.006758\,cos\,2(n-1)2\pi/365 + 0.000907\,sin\,2(n-1)2\pi/365 - 0.002679\,cos\,3(n-1)2\pi/365$$
$$0.00148\,sin\,3(n-1)2\pi/365 \quad (3.4)$$

Where n is the number of days of the year and solar declination can be calculated for any day of the year. The variation of solar declination, aperture area and power for a 10 m^2 Scheffler concentrator is shown in Fig. 3.5.

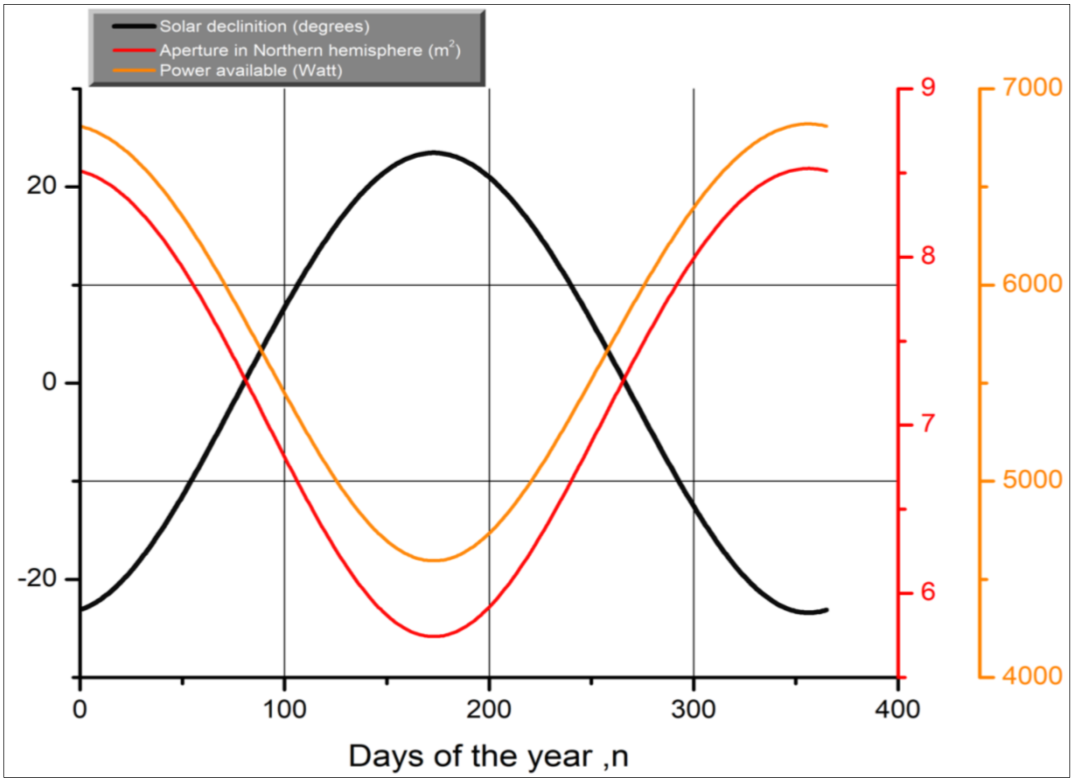

Figure 3.5: Solar declination, aperture area (m2) and solar power (W) available from 10 m2 fixed focus concentrator at site

For the standing reflectors, the maximum and minimum aperture area is calculated to be 8.52 and 5.74 m^2 during winter and summer solstice, respectively. However, standing reflectors exhibit similar aperture area (7.27 m^2) at equinox as shown in Fig. 3.6. The energy absorption of standing Scheffler reflectors for the same intensity of beam radiation is higher in winter as compared to the summer. The provision of fixed focus near the ground level as well as more aperture area in winter as compared to summer for the generation of constant power output throughout the year with proportionally less and more solar insolation available makes this versatile solar concentrator design even more attractive particularly in tropical regions of the northern hemisphere.

It is also evident from Fig. 3.4 that 10 m^2 solar concentrator can take 8 kW input power at 800 Wm^{-2} beam radiation if all the surface area is fully utilized. It is also clear from the Figure that the power available on reflector varies from 6819 W in winter solstice to 4593 W in summer solstice while 5794 W at equinox due to change in aperture area as a result of changing solar declination.

3.3.7 Useful Energy Available at Solar Concentrator

The energy distribution at paraboloidal concentrator is shown on Point No.2 (Fig. 3.5). The useful rate of radiant energy available ($Q'_{(c,u)}$) on the face of Scheffler concentrator can be calculated by the following formula.

$$Q'_{(c,u)} = A_a G_b - Q'_{c(l,opt)} \tag{3.5}$$

Where, $Q'_{(c,u)}$ is the optical losses from SC/reflector. Optical losses from SC include losses due to poor reflectance either due to material or improper surface cleanability, lack of precision of concentrator profiles to approximate the required part of paraboloid as well as inadequacy in daily and seasonal tracking. Glass mirrors with reflectivity greater than 90% were used as reflecting material. Various experiments were conducted to check the accuracy of the reflected radiation on targeted focus and it was invested that 10-15% radiation is not available on the stationary targeted receive area and this loss is also considered as optical loss. It was also investigated that more accurate focus was available at midday as compared to morning or evening time. So, the useful energy component is taken as 85% and showing the fraction of energy available from the reflected radiation from the Scheffler concentrator. (Munir & Hensel, 2010). The total useful energy available from the SC is calculated by multiplying specific reflectance with the fraction of solar radiation available on targeted focus and is found to be 0.68.

3.3.8 Useful Energy Available and Losses at Steam Receiver

Point No.3 (Fig. 3.5) indicates the useful energy available at receiver and losses from the receiver. Major losses from the steam receiver include optical and thermal losses as given in Equation.

$$Q'_{r(u)} = Q'_{c(u)} - Q'_{r(l,opt)} - Q'_{r(l,th)} \tag{3.6}$$

Where is the optical losses from the receiver and is the thermal losses from the receiver.

In case of receiver, the optical losses are due to lack of absorbance of reflected radiation from the SC on the top side of the receiver. The receiver was painted black with high absorbent solar mat. The thermal losses include losses due to conduction, convection and radiation from the receiver. The top part of the receiver is exposed to reflected solar radiation from the SC.

3.3.9 Useful Energy Available and Losses at Milk Pasteurizer

The useful rate of heat energy available at the pasteurizer tank for milk pasteurization is given as:

$$Q'_{p(u)} = Q'_{r(u)} - Q'_{p(l,th)} \tag{3.7}$$

Where the thermal losses from the receiver and these losses is due to conduction, convection and radiation losses. This area is the cylindrical area of the pasteurizer which is insulated with 50 mm rock wool insulation as shown in Fig. 3.4.

A complete algorithm was prepared and output of thermal losses is calculated by putting input data (boundary temperature conditions, material characteristics, geometry and characteristics) in the algorithm made for milk pasteurizer. The milk pasteurizer (⌀ 432 x 559 mm) was insulated from all bottom and lateral sides with 50 mm polyurethane insulation material (thermal conductivity: 0.026 $Wm^{-1}k^{-1}$).

Wet steam from steam receiver was used to quickly pasteurize milk at 65°C by utilizing the latent heat of vaporization (2257 $kJkg^{-1}K^{-1}$) of water.

3.3.10 Thermal Losses Calculation of the Steam Receiver and Milk Pasteurizer

For all kinds of calculations, ambient temperature, space temperature was assumed as 25 and 15 respectively. The steady state heat transfer (φ) through a cylindrical layer that are exposed to convection on both sides to fluids is given as (Cengel, 2006):

$$\varphi = \frac{T_{in} - T_{amb}}{R_{cond} + R_{conv}} \qquad (3.8)$$

Where, T_{in} represents the temperature inside the milk pasteurizer, T_{amb} stands for ambient temperature, R_{cond} denotes the conduction resistance, R_{conv} represents convection resistance

Thermal conduction resistance for the cylindrical part of pasteurizer is calculated by the following relation (Cengel, 2006):

$$R_{cond} = \frac{1}{2\pi \lambda L} ln\left(\frac{r_{ext}}{r_{int}}\right) \qquad (3.9)$$

where λ represents the thermal conductivity of the material used, L stands for the lateral length of the cylindrical pasteurizer/receiver, r_{ext} is the external radius of the cylindrical pasteurizer, r_{int} is the internal radius of the cylindrical pasteurizer or receiver.

The conduction resistance of the circular part of pasteurizer or receiver is calculated by the following relation (Cengel, 2006):

$$R_{cond} = \frac{t}{\lambda A} \qquad (3.10)$$

Where 't' is the wall thickness of circular section of pasteurizer or receiver, A is the cross-sectional area of the circular section of pasteurizer or steam receiver bottom.

With insulation, the conductive resistance for multilayered plane wall and cylindrical segments is calculated by adding the conductive resistance for all layers and is generalized as:

$$R_{cond} = \sum R_{cond}^{i} \qquad (3.11)$$

Where "*i*" indicates any layer of stainless steel, insulation material and cover plate and with different thermal conductivities and thicknesses.

Convection resistance is calculated by the following relation.

$$R_{conv} = \frac{1}{hS} \qquad (3.12)$$

Radiation heat losses are calculated by the following relation

$$Radiation\ losses = \varepsilon\ \delta\ S\left(T_{ext}^{4} - T_{space}^{4}\right) \qquad (3.13)$$

Where *ε* is the emissivity, *δ* is the Stephen Boltzmann constant, T_{space} is the space temperature (K), T_{ext} is the external area temperature (K) and is calculated by the following formula.

$$T_{ext} = T_{amb} + \varphi R_{conv} \qquad (3.14)$$

By substituting the value of T_{ext} in Eq. (2.13), the total heat losses by radiations are calculated. By adding all the losses, the total losses of the system can be calculated

3.3.11 Available Energy and Losses Using Evacuated Tube Collector

The input energy for evacuated tube collector is given by the following Equation

$$G = \frac{I_t A_c}{1000} \qquad (3.15)$$

Where *G* is the rate of incident solar energy at collector (kW), I_t is the total solar irradiance (W/m^2), A_c is the surface area of evacuated tube collector (m^2) and is calculated by multiplying effective tube length (exposed to solar radiation) by its diameter (aperture) and number of tubes.

The thermal efficiency of solar evacuated tube collector depends on solar input energy, losses and heat transferred to the working fluid and it can be taken in the rage of 70–80%. Main objective of the study is the thermal analysis of solar milk pasteurization and heat is transferred to glycol and water solution from ETC header and then this hot water is used to heat the outer shell of the cylindrical pasteurizer from the hot water storage tank as shown in Fig. 3.7. So, the amount of heat energy ($Q`_F$) transferred to working fluid (water + glycol solution) and then to milk can be estimated by multiplying the mass flow rate with the specific heat of the fluid and change in temperature. The additional benefit of this system is the heat energy storage in hot water tank which can be used for effective milk pasteurization even during low solar radiations hours. The complete schematic of milk pasteurization working on ETC is presented in Fig. 3.6.

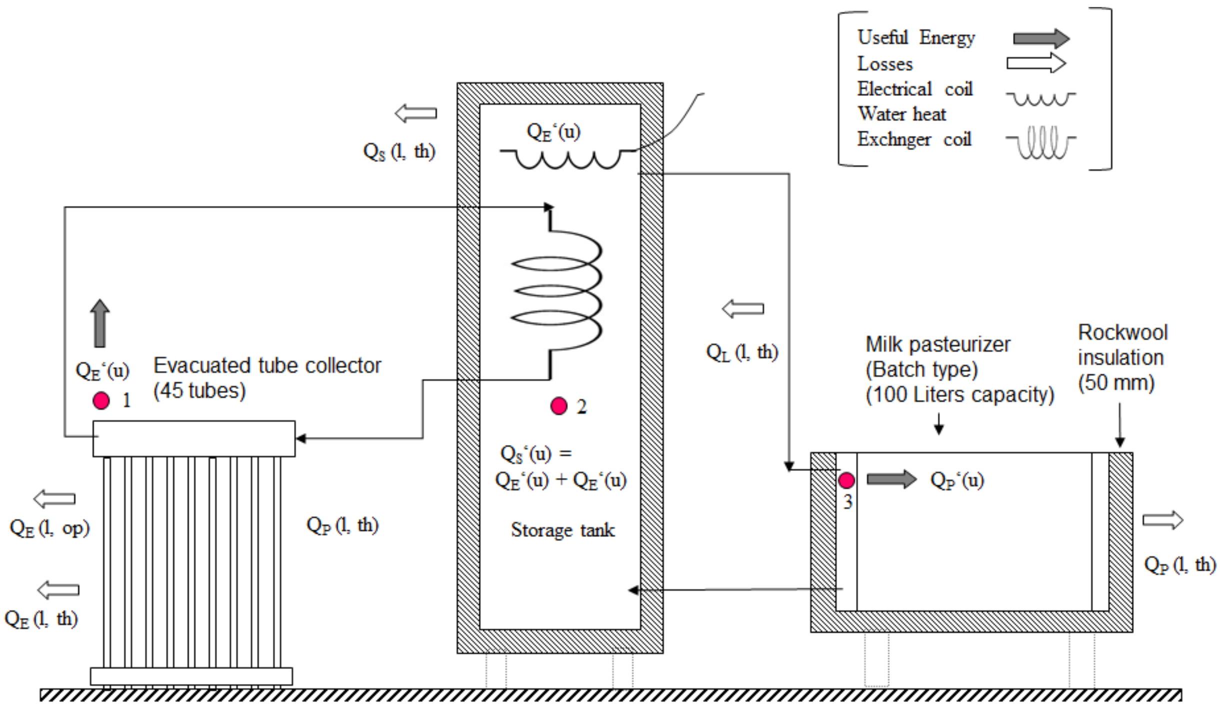

Figure 3.6: Schematic layout of milk pasteurization working on ETC and thermal storage

The amount of energy required to raise the temperature of 150-liter water in the storage tank from ambient temperature (25°C) to almost 90˚C can be calculated using the following equation

$$\dot{Q}`_W` = mC_p(\Delta T) \quad (3.16)$$

Where Q` is the rate of heat energy need to be transferred to water, m is mass of water (kg or liter), Cp is specific heat capacity of water (kJ/kg. C)

Similarly, the amount of energy required to raise the temperature of 100L milk ($Q`_M$) up to temperature difference of 40°C can be estimated in similar fashion.

The total useful energy received from ETC '$Q_{E'(u)}$' and useful energy available for milk pasteurization tank '$Q_{P'(u)}$' are calculated to be 5460 W and 4070 W respectively. Total thermal losses '$Q_{L(l, th)}$' from 18.8 m length piping (⌀25.4 mm) and fittings connecting all these three components (pasteurizer, hot water tank and ETC) is estimated to be 638 W.

Thermal losses from hot water tank ' $Q_{S(l, th)}$' and the pasteurizer '$Q_{P(l, th)}$ were calculated to be 116 and 90 W respectively.

3.4. Field Experiments of Milk Pasteurization Using Solar Concentrator

Many experiments were conducted for milk pasteurization using SC and process curve of one of the experiments is presented in Figure 3.7. It is evident that under the constant range of beam radiation, pasteurization process is quite smooth with gradual increase in temperature and the process completed in 80 minutes to reach a temperature of 63°C. The average value of beam radiation was recorded to be 734 Wm^{-2} during pasteurization process.

The temperature was maintained for a period of 30 minutes more to meet WHO standards and steam flow rate was maintained accordingly. The average power consumed was recorded to be 2.67 kW to reach this pasteurization temperature of 63°C and experiment was started from 30°C as shown in Figure 3.8. The total energy required for the pasteurization of 100L batch of milk was calculated to be 3.566 kWh. The average input solar power and total solar energy available on 6.75 m^2 aperture area (for the month of August) of SC was recorded to be 4.95 kW and 6.60 kWh respectively during 80 minutes of pasteurization time with 54% efficiency. The results show that solar milk pasteurization can be successfully done using SC.

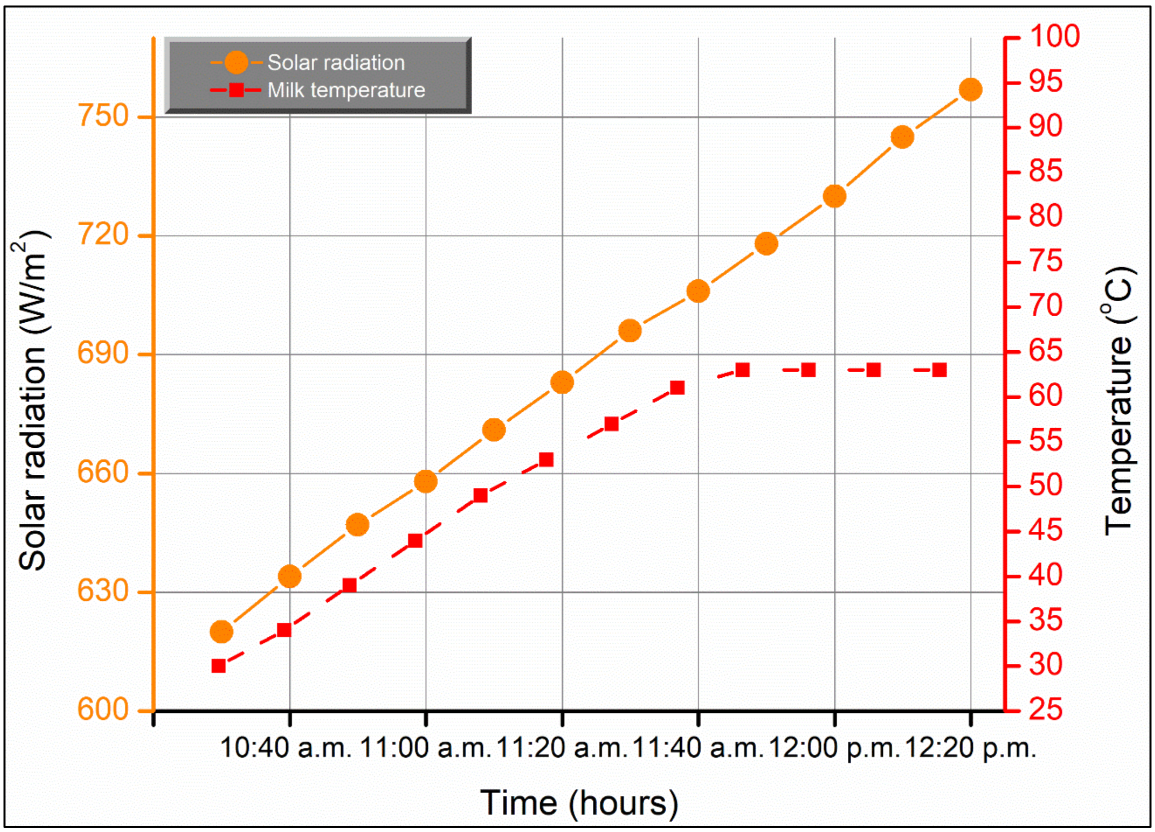

Figure 3.7: Temperature variation during milk pasteurization under varying solar irradiance using SC

3.4.1 Field experiments of milk pasteurization using Evacuated Tube Collector

Figure 3.9 shows the solar irradiance, temperature of glycol-water mixture, water temperature and temperature of milk. It is evident from the Figure that under the constant range of solar radiation, the glycol solution temperature increased rapidly and reaches its maximum value of 100°C and maintains almost at this temperature throughout the experiment. It is also evident from the Figure 3.9 that hot water temperature in the storage tank increases slowly and reaches up to 80°C. The average GHI during pasteurization process was recorded to be 780 Wm^{-2} and the average input power on aperture area (4.695 m^2) of ETC was recorded to be 3.66 kW and total input energy was found to be 5.49 kWh to reach the pasteurization temperature in 90 minutes. Power utilized during this test was calculated to be 2.615 kW with total used energy of 3.91 kWh in 1.5 hour. The efficiency of the complete system was found to be 71.41% under the existing set up of the milk pasteurization system working on ETC. Similar results were obtained from other experiments.

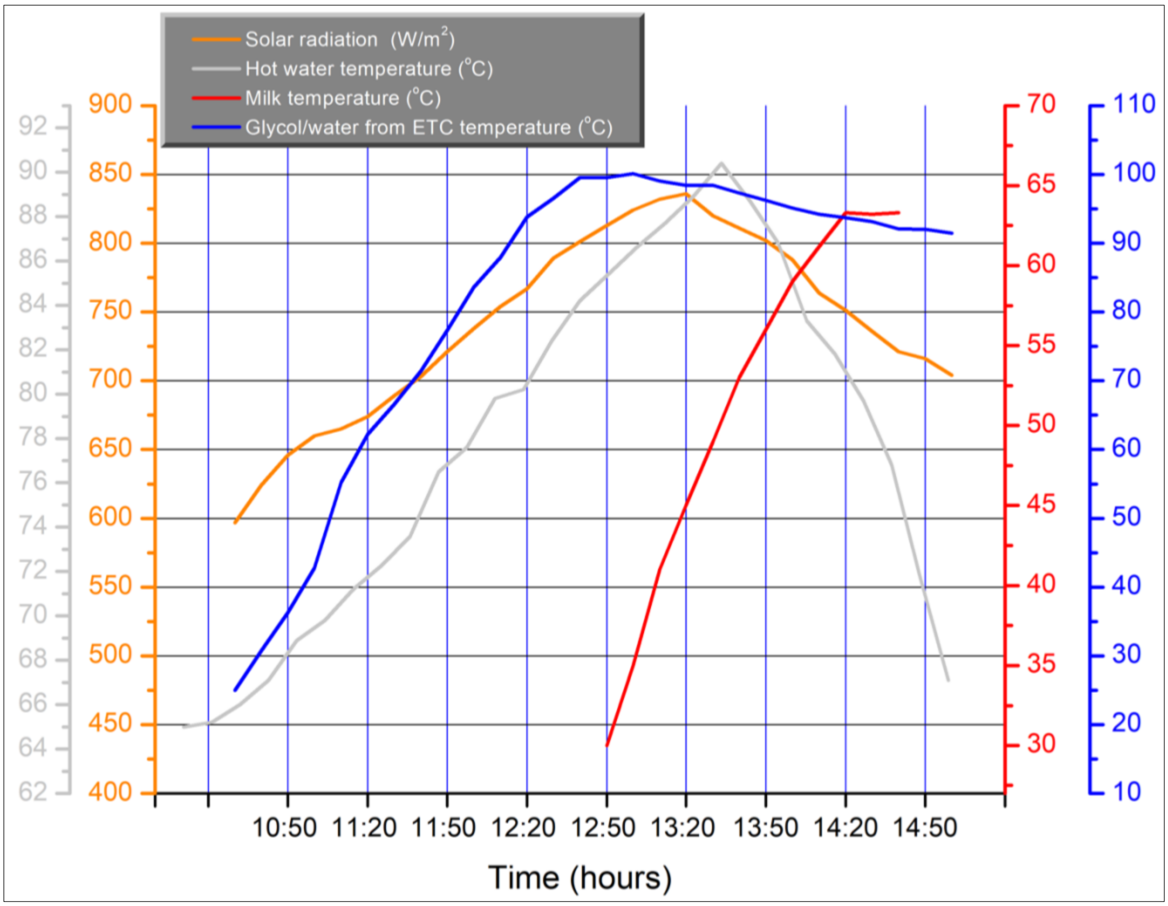

Figure 3.8: Change in hot water, glycol solution and milk temperature and solar irradiance during milk pasteurization using ETC

3.4.2 Power distribution in milk pasteurization using Solar Concentrator

Energy balance of the milk pasteurizer using available parameters and specification of the milk pasteurizer different losses were calculated as shown in Figure 3.10. In order to perform a detail thermal analysis, the entire system has been divided into different segments (solar concentrator, receiver, piping and fitting and the pasteurizer) to describe the power losses occurred in working fluid during pasteurization process.

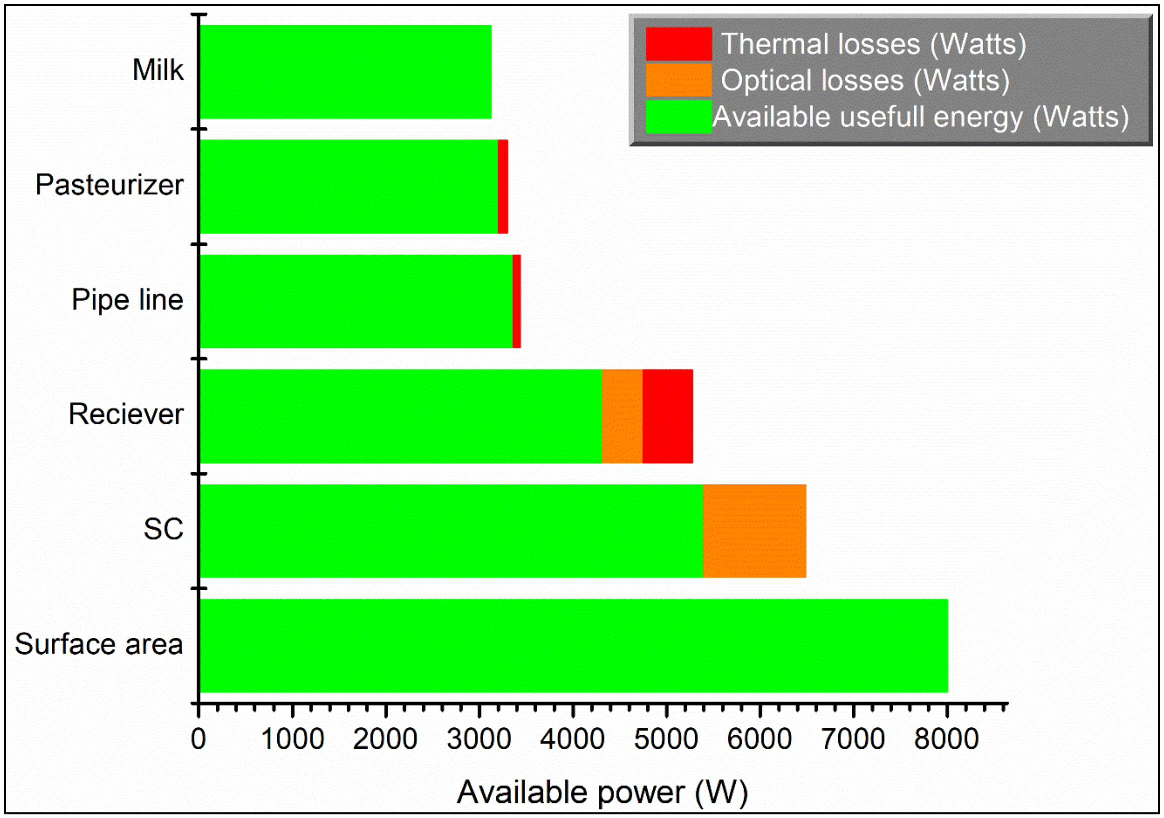

Figure 3.9: Expected energy distribution per unit time from solar milk pasteurizer (for the standing reflectors in the northern hemisphere on Aug, 31 for 800 W m-2)

The rate of useful thermal energy available and losses from the current solar milk pasteurization prototype using SC have already been indicated by black and white arrows in Figure 3.10. Due to changing aperture area of the Scheffler reflector, input data set was taken for August 31 (one sample day of August for comparison when most field experiments were conducted) with average beam radiation 800 W m^{-2} under similar conditions in order to evaluate and compare two solar based milk pasteurization systems under identical premergers. Total power available using full surface area (8 m^2) of SC is 8000 W while available power (G_b) is equal to the product of average beam radiation (800 Wm^{-2}) and aperture area (6.75 m^2) available under prevailing condition to have a fixed focus on ground level and this value is found to be 5403 W. Out of this available power, the optical losses ($Q'_{c(l,opt)}$) are found to be 1081 W (20%) and available power ($Q'_{c(U)}$) in the radiation after reflecting from SC is calculated to be 4322 W and this power is available at steam receiver. The optical losses from steam receiver (($Q'_{R(l,opt)}$) are found to be 432 W and thermal losses ($Q'_{c(l,th)}$) are 521 W. The useful power from receiver was calculated to be 3369 W by using Eq. (6). The line losses from piping and fittings are found to be 303 W and available energy to pasteurizer was found to be 3066 W. The thermal losses at pasteurizer section ($Q'_{P(l,th)}$) are found to be 90 W and useful power (($Q'_{c(U)}$) available to milk is calculate to be 2976 W. The theoretical efficiency was calculated as 55% with the existing system installed for milk pasteurization.

3.4.3 Power distribution for milk pasteurization using Evacuated Tube Collector

Complete power balance of the milk pasteurizer using ETC has been presented Figure 4.6. The average solar radiant power received at ETC ($Q_{E'(u)}$) was found to be 3.756 kW and useful energy available for milk pasteurization tank 'QP'(u)' are calculated to be 5.63 kWh. Optical losses from ETC ($Q'_{E(l,opt)}$) were found to be 376 W and these were in the form of transmittance and absorbance losses. Thermal losses from hot water tank $Q'_{T(l,th)}$, pipe line ($Q'_{L(l,th)}$) and pasteurizers ($Q'_{c(l,th)}$) were found to be 115, 359 and 90 respectively and showing that about 15% losses are being taking place as thermal losses. The theoretical efficiency of the system was found to be about 75%.

3.4.4 Comparative analysis of Solar Concentrator and Evacuated Tube Collector

This research is focused on thermal analysis and comparison of heating sources used for effective milk pasteurization. Fig. 3.11 shows energy distribution of solar pasteurization system couples with SC and ETC both with respect to their gross and aperture areas.

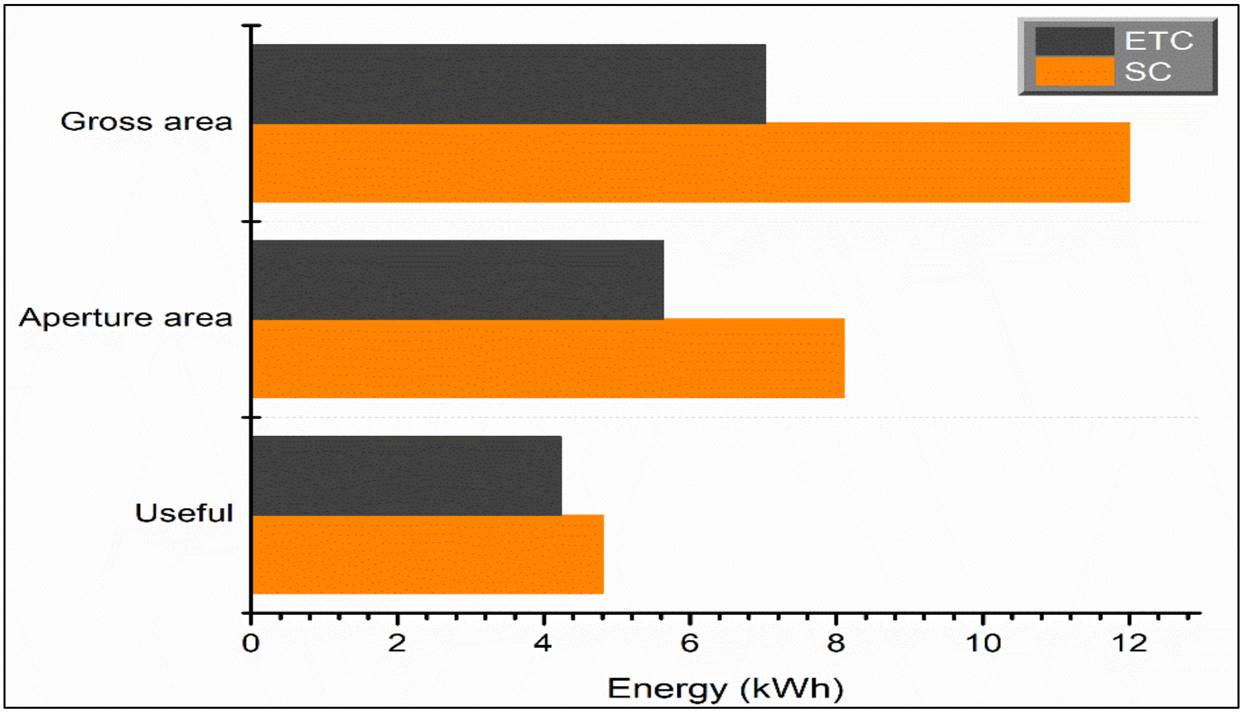

Figure 3.10: Input energy available on gross area of SC and ETC

It is evident from Figure 3.10 that the input energy available on gross areas of SC and ETC were calculated to be 12 kWh and 7.02 kWh respectively while energy values available on aperture area for SC and ETC were calculated to be 8.12 and 5.63 kWh respectively during the pasteurization process. Energy required to pasteurize 100L of milk were calculated to be 4.68 and 4.22 kWh respectively for a temperature difference of 35-40°C. Under practical conditions, heat energy consumed for the milk pasteurization system coupled with SC and ETC was recoded to be 3.56 kWh and 3.91 kWh respectively; this value lies from 3.78 – 4.32 kWh to pasteurize 100L of milk for a temperature difference of 35-40°C. It is also worth mentioning here that the total energy available (7.02 kWh) from 7.75 m^2 aperture area of SC for a sunny day of August 31 having average bean radiation as 800 Wm^{-2}. However, this energy value goes on changing in case of SC as the aperture area ranges from 6.819 m^2 (Winter solstice) to 4.593 m^2 (summer solstice). There is a big comprise on reduction of aperture area due to seasonal variation of sun position (solar declination) in summer that resulted in reduction in power in spite of larger surface area of the SC. On the other hand, aperture area remains the same to ensure uniform power through the year under the same range of GHI. Moreover, more power can be harvested using ETC with comparatively less area loss and space required to pasteurize milk with solar energy. For the milk pasteurization, ETC also provided excellent opportunity to process the milk even during slight fluctuation in sunny conditions and the system utilizes the stored energy which always remains available in the storage tank for the consistency of the process. Moreover, ETC can perform efficiently without using any tracking system, complex design consideration and more area needed as required in case of SC. ETC provides more flexibility for increasing or decreasing heat sources by simply addition or removal glass tubes according to quantity of milk to be processed.

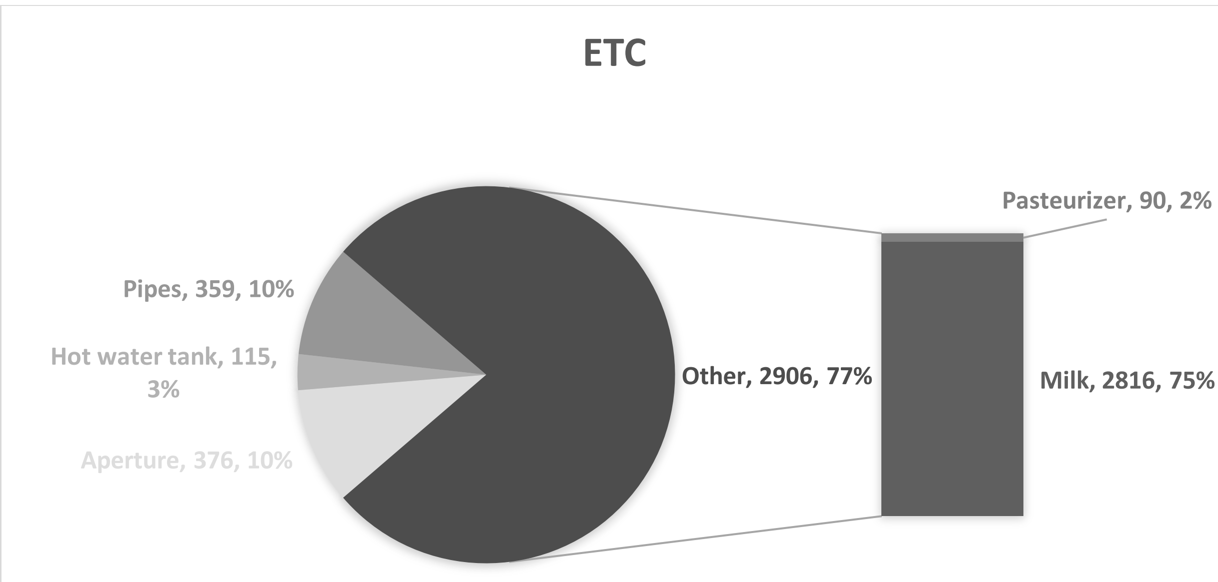

Figure 3.11: Power losses during pasteurization for ETC

The complete breakup of optical and thermal losses for SC and ETC are given in Figure 3.11 and 3.12. The rate of heat energy losses at pasteurizer, receiver, pipes and optical losses are shown for both technologies. The results have shown that optical losses of the reflector and receiver for SC were found to be 1083 W and 953 W respectively with total losses of 2033 W. This huge difference in optical losses in SC is due to lack of specific reflectance and absorbance of SC and receiver as well as in inadequacy of precision of manufacturing and tracking inefficiency. On the other hand, optical losses of ETC were found to be 376 W only and this minor loss is due to the transmittance of the cover glass and absorbance of the absorber tube.

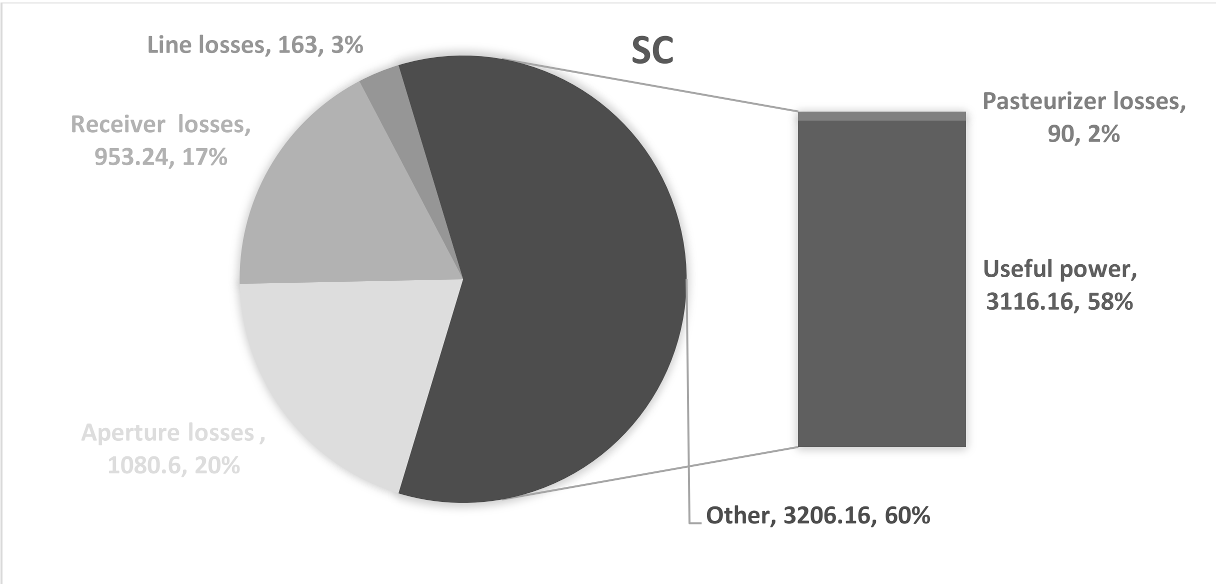

Figure 3.12: Power losses during Pasteurization for SC and ETC

In case of thermal losses, both the system exhibited the same losses of 90 W from pasteurizer contributing only 2% of the total and this is actually due to good insulation of the milk pasteurizers from bottom as well as from the lateral side. The thermal losses from hot water storage tank is calculated to be 116 W. However, pipe line losses were calculated to be 161 W (3%) and 359 W (10%) for SC and ETC respectively. The available rate of useful energy figures was found to be 3118 and 2816 W, respectively.

Fig. 3.13 illustrates the efficiency comparison of predicted and actual values of both the heating sources (SC and ETC).

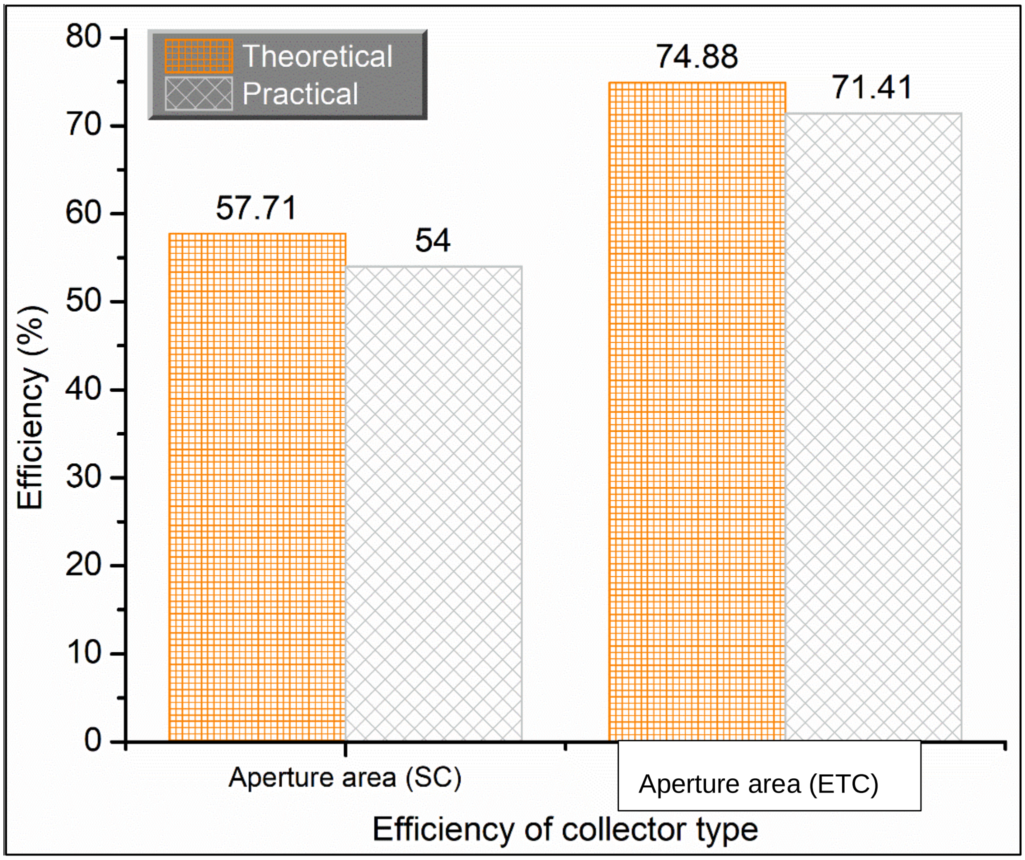

Figure 3.13: Efficiency comparison of milk pasteurization systems working on SC and ETC (Theoretical and practical)

One to one efficiency comparison is presented in Figure 3.13. The predicted value of efficiency for SC and ETC were found to be 57.71 and 74.88% respectively. The efficiency values under field conditions for SC and ETC were found to be 54 and 71.41% respectively. In both cases (Theoretical and practical), efficiency of ETC is significantly higher than that of SC. This is due to the fact that the optical losses and thermal losses in ETC are very less as compare to that of SC. This is main limitation of using a SC due to complicated and inclined design as well as lack of accuracy while focusing the reflected rays on receiver during tracking under practical condition. It is also evident from Figure 3.11 that the practical values for both the cases are almost same but a slight on lower side as compared to theoretical ones. This is due to the reason that some unaccountable losses (due to change in wind velocity, ambient conditions, and the values of physical and thermal parameters used in calculation do not match the actual conditions.

Solar based milk pasteurizer enables decentralized preservation of milk quality at zero or minimum operating cost, particularly in remote areas of Pakistan. With the introduction of innovative and efficient medium temperature solar technologies, two approaches can be conveniently used to accomplish pasteurization i.e., SC and ETC. The present study focused on a widespread comparative thermal analysis of above-mentioned techniques for a solar-driven milk pasteurization unit. The detailed thermal analyses of both the solar based systems were conducted to investigate the useful energy and losses during the process of milk pasteurization. The available energy values were found to be 8.11 and 5.63 kWh at the aperture areas of SC and ETC, respectively. Energy required to pasteurize 100L of milk were calculated to be 4.68 and 4.22 kWh respectively for a temperature difference of 35-40°C. Some of the recent studies regarding ETC, Shafieian et al. (2019) proposed that the temperature of the solar working fluid increased as the number of glass tubes increased, however, the temperature increase rate decreased and became comparatively insignificant for the number of tubes greater than 25 to 30. They attributed this reduced or even stable temperature increase to increased surface area and consequently increasing absorption capacity of ETC. Our findings are completely inconsistent with the above-mentioned findings as we observed that the temperature of working fluid (water in our case) increases with increase in number of tubes. The temperature was restricted to 40 ºC in case of 15 tubes, however, a significant rise was noted as the number of tubes increased to 45. For Faisalabad region during bright sunny summer days, the above-mentioned fact is true which slightly fluctuates in case of a cloudy/dense day. We also noted that for this region, rate of increasing temperature stabilizes at 45 tubes as opposed to the Perth (Australia) where Shafieian et al. (2019) made the experimental setup with 25 tubes. In our case we have employed a storage tank (fully insulated with PU) and extra energy is stored in the storage tank which can be used for next batches.

Another important factor involves the regional wind velocity of the study area. The average wind velocity for the Faisalabad region is 2 m/s. We observed a negligible effect on temperature variation in ETC. Similarly, Du et al. (2013) prepared a platform for studying the performance of a HPSC in a solar water heating system. The obtained results including collector outlet temperature, instantaneous efficiency, and pressure drop were presented in detail. The maximum achieved efficiency of the collector was 60 % which occurred at the solar radiation of 860 W/m^2. Whereas, in our research the efficiencies for SC and ETC were recorded to be 58 % and 74 % respectively under the average solar radiation of 750 W/m^2. These figures conclude that the efficiency of improved milk pasteurization employing ETC, and Sc are greater than the research conducted by Du et al. (2013).

Rassamakin et al. (2013) proposed the application of specially extruded aluminum heat pipes in the HPSC of a solar water heating system to reduce the contact thermal resistance. Under practical conditions, heat energy consumed for the milk pasteurization system coupled with SC and ETC was recorded to be 3.56 kWh and 3.91 kWh respectively; this value lies from 3.78 – 4.32 kWh to pasteurize 100L of milk for a temperature difference of 35-40 °C. The predicted value of efficiency for SC and ETC were found to be 57.71 and 74.88 % respectively. The efficiency values under field conditions for SC and ETC were found to be 54 and 71.41 % respectively. In both cases (theoretical and practical), efficiency of ETC is significantly higher than that of SC. Since the optical losses and thermal losses in ETC are very less as compared to that of SC. The heat energy losses per unit time (W) were also calculated in terms of optical losses study concluded that both the systems can be effectively utilized for the milk pasteurization; however, ETC based solar milk pasteurization system proved to be more efficient, simpler in design, cheaper, stable, compact, portable, and cost effective and provides excellent opportunity for decentralized milk processing.

3.5 Conclusion

Milk processing in rural areas needs efficient decentralized renewable energy solutions not only for handling the fresh milk at farm level but also providing a cheaper sustainable solution to small entrepreneur. In this study, a detailed thermal analysis has been carried out of a milk pasteurization system coupled with Scheffler fixed focus concentrator and evacuated tube collector not only to investigate the useful energy and losses during the process of milk pasteurization but mainly to present a comparison of these two high-temperature applications. It would help designers to make the right decision solar energy applications in dairy sector. The available energy was estimated to be 8.10 and 5.63 kWh at the aperture areas of SC and ETC, respectively. Under the constant range of solar radiations (GHI), the pasteurization process is quite smooth with gradual increase in temperature and process completed in 80-90 minutes to reach a temperature of 63°C from ambient temperature. The total power consumed was recorded to be 2.67 kW to reach this pasteurization temperature. The total energy required for the pasteurization of 100L batch of milk is 3.57 kWh. Though results showed that solar milk pasteurization can be successfully done using SC yet under the average beam radiation range of 686 Wm^{-2}, the overall efficiency of the system was found to be 58%. On the other side, in case of ETC, the overall efficiency of the system was found to be 74%. These results are in accordance with results obtained from predicted values (54% for SC and 71% for ETC) showing the reliability of the developed algorithm. Research concluded that both systems can be effectively used for the milk pasteurization system, however, the system coupled with ETC is more efficient, simple in design and provides thermal storage to continue the process under varying weather conditions.

Acknowledgment

The authors gratefully acknowledge the International center for decent work and development (ICDD) University of Kassel Germany for funding of this project. We would also like to appreciate Deutscher Akademischer Austauschdienst (DAAD) and Fachgebiet Agrartechnik Uni Kassel Witzenhausen (AGT) for their cooperation and support during pre and post research activities for the present study. Finally, we would like to acknowledge Department of Energy Systems Engineering, University of Agriculture Faisalabad Pakistan (ESE-UAF) for providing technical assistance and site place for the development and installation of systems used for the project.

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4.0 Improved solar milk chilling system using variable refrigerant flow technology (VRF).

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4.1 Abstract

Being a natural liquid food, milk is a complete nutritional diet containing all of the essential minerals such as protein, fat and vitamins. However, improper post milking handling and storage resulting in wastage due to microorganisms and bacterial multiplication. Fresh milk was spoiled due to increased temperature in developing countries. While using solar PV, minimizing torque load of the cooling machines was big challenge for the smooth functioning of the milk chilling system especially for the conventional (reciprocating) type of compressors; variable refrigerant flow (VRF) technology not only solved toque load problem but also reduced the size of peak power requirement of PV array. This system comprises a milk-chilling tank (200-liter capacity) coupled with one tonne of refrigeration unit powered by PV panels (2kWp) and employing VRF technology to make system more energy efficient by minimizing the torque load. Experiments were conducted using different batch sizes (50L, 100L, 150L and 200L) to cool down the raw milk from 30ºC to 4ºC. During the optimization phase, the comparative power required to run various types of compressors (reciprocating, rotary with capacitor and rotary with VRF) were found to be 1.8 kW, 1.2 kW and 0.8 kW respectively whereas the torque loads were noted to be 3.3 kW, 1.6 kW and zero kW. The experimental and modeled predicted power consumption and chilling time under different batch sizes revealed good correlation coefficients (R^2 = 0.99, $P < 0.0001$). It was found that about one-tonne of refrigeration unit is sufficient to chill 200 liters of milk up to 4ºC within less than two hours as per WHO standards for on farm processing of milk.

Keywords: Solar energy; variant refrigerant flow technology, Decentralized milk chilling, torque load minimizing

4.2 Introduction

Raw milk is considered as a tremendous medium for contagious growth of bacteria's and other pathogens which soon get accelerate when stored at ambient temperature. Fresh milk is spoiled due to increased temperature and in developing countries, farmers have to sell their products at very low market prices due to non-availability of processing facilities. With the introduction of demand based renewable energy technologies, it is possible to use this energy in adding value to fresh milk.

Pakistan stands fourth in the list of milk producing countries in the world after USA, China and India (Hussain et al., 2014) but a significant amount of raw milk is spoiled due to lack of awareness and processing facilities available in rural areas. Moreover, more than 50% of rural population has no access to neither electricity nor fossil fuel availability to preserve and process the raw milk effectively. On the other hand, there are about 72 Million animals in the form of cows and buffaloes in Pakistan producing about 42 billion litres of milk annually (Shahid et al., 2012). As a result, the farmers have to sell the raw milk at low price due to absence of post milking facilities. Solar energy, not only, provides an extraordinary opportunity to address the decentralized and on-farm processing of milk for value addition but also can provide income generation opportunities in rural community of Pakistan. At the same time, cost of production of processed/pasteurized milk will be far less than the commercial milk production system. The preservation of raw milk for a longer duration would lead to promotion of dairy sector in poor rural community. Dairy sector of Pakistan is an inevitable reality for socio-economic development and the growth of rural economy. Dairying is considered as a secondary source of income after farming for rural communities. It may generate not only the employment and income opportunities next to agriculture, but also promising the supply chain of quality milk products in rural and urban communities as well. Due to increasing awareness on milk quality and standards set by WHO to minimize infant and adult diseases due to poor quality of unprocessed milk, it has become imperative and mandatory to process the milk before selling to the consumers.

Milk is a composite food promising various nutrients required for daily human nourishment regarding nutrients (FAO, 2013). Milk is enriched with numerous nutrients naturally for human body which makes significant contribution in the form of calcium, magnesium, selenium, riboflavin, vitamin B12 and pantothenic acid (vitamin B5). Human body needs nutrition development for whole life particularly in childhood which can be satisfied by milk and dairy products. However, raw fresh milk is greatly vulnerable to the spoilage being an excellent growth media for the microorganisms. Milk quality declines promptly without treatment through the application of cooling or/and heating processes (FAO, 2000). Spoiled milk may lead to illness and economic loss respectively, for its consumers and producers. The raw milk can easily get spoiled due to bacterial infection, if it exposes to high temperature for long duration. Therefore, it is necessary to maintain the temperature soon after the completion of milking process. The bacterial reproduction can be minimized in terms of content if it is stored at lower temperature (Sharma et al., 2003) The preheating treatment is inevitable to get the quality milk by killing bacteria as final product to end-user. Heating of milk at precise temperature kills bacteria and harmful microorganisms. Similarly, cooling milk slows down bacterial growth, reducing spoilage and therefore increasing farmer income, and also ensuring safe milk for the consumers.

Asian and African countries produce on-farm milk on a smaller scale as compared to European and American countries, about 10–15 L milk on an average basis over each farm. Milk is collected from 15-25 villages but chilling facilities are usually provided at a few places to cater the milk efficiently. Chilling facilities and milk production unit might be situated at a distance of about 10–12 km, which takes 2 hours on an average basis to reach milk from the point of production to the chilling unit. Raw milk undergoes several chemical changes during this period. Immediate chilling of raw milk on the farm is recommended due to perishable nature of the milk, however, developing countries are unable to get such facilities practically due to several reasons. Raw milk is chilled up to 4°C to increase the shelf life of raw milk, which is a commonly adopted practice worldwide. Shortage of electricity is one of the major reasons in developing countries, to get chilling facilities at the milk collection units. So, the chilling unit operated at the cheapest energy source is unavailable at the local farm scales to meet the efficient milk storage techniques.

In order to meet the energy requirement for the cooling of milk, use of renewable energy at milk production sites would be an effective way to maintain the quality of produced milk timely. Few studies have already been addressed the efficient use of renewable energy for chilling process such as the use of conventional vapor-compression cycles in combination with PV panels and thermal solar systems leads to the most attractive economical solution so far for chilling process (Infante Ferreira and Kim, 2013; Sarbu and Sebarchievici, 2013; Torres-Toledo et al., 2014). Some studies regarding milk preservation using solar system have shown the adaptation of commercial refrigerators to work with DC-compressors as discussed by (Kaplanis and Papanastasiou, 2006). They observed similar COPs for AC refrigerators equipped with inverters as of (Kattakayamand Srinivasan, 2000; Modi et al., 2009), and those using DC-compressors (Deshmukh and Kalbande, 2015; Ekren et al., 2011; Kaplanis and Papanastasiou, 2006). The performance monitoring of the whole solar system has been recently described in Tina and Grasso (2014). Similarly, performance evaluation studied by (Edwin and Joseph Sekhar, 2014; Murphy et al., 2013) on milk cooling systems focused on fast cooling to assure milk quality and techno-economic aspects for its implementation in remote regions. Some studies were primarily focused on different material and cooling configuration evaluation (Torres-Toledo, 2013; Torres-Toledo et al., 2014).

All the above-mentioned updated studies were based on rendering a chilling solution within less time, mainly restricted to single compressor type or less battery usage, for preservation of small quantity of milk but lacking the main problem of torque load challenge for solar PV system and selection of an optimally design solar system. The present study investigates the use of refrigerant flow technology to minimize the torque load and the conventional compressor (reciprocating) replaced by rotary type to make system more energy efficient. This not only provides the solution for chilling only but also enables the selection of a best compressor based on minimum torque load employing variable refrigerant technology for 50 to 200 liters of milk batch sizes with high COP using real time data recorded during experiments. This study investigates variable refrigeration flow (VRF) coupled with solar PV system using three types of technologies with two type of compressors. Keeping in view the aforementioned facts, the present work was aimed to design milk-chilling unit as a decentralized application. Secondly, to investigate the feasibility of refrigeration technology and the batch capacity in relation with solar energy utilization is evaluated. The study would be helpful for the stakeholders for the value addition of milk and to address the issue of milk spoilage.

4.3 Study area

According to the Food and Agriculture Organization of the United Nations (FAO) roughly one-third (by weight) of global food production is lost or wasted every year (Bareille et al., 2015). Nestle and Deliotte conducted a case study in Pakistan based on the milk spoilage in 2016 due to the following reason (Tostivint et al., 2016):It is one of the most complex dairy value chains that Nestle has Pakistan is also among the top 5 countries of Nestle’s supply of fresh milk globally. The present study has been carried out at the same place where annual cow and buffalo milk production in Pakistan approached 38.3 Mt in 2012 (64% from buffaloes) ranking the country 4th globally, after India, USA and China. The major milk production is rendered about 80% from rural areas followed by sub urban and urban areas for the rest (Fusions, 2014; ICDD, 2013). Mostly villagers lack access to the milk market and produce milk to meet family requirements carrying an average herd consisting of around three buffaloes, and milk yield per animal is ca. 3 kg/day (FAO 2011 a). These people need a chilling source which should be closed to their vicinity and economical to meet their financial status.

4.4 Material and methods

The whole unit of milk chiller has been developed and fabricated in the Energy Systems Engineering Workshop, Faculty of Agricultural Engineering & Technology, and University of Agriculture Faisalabad (UAF) Pakistan in collaboration with Dairy Industries, Okara.

4.4.1 Design of solar based chiller

In the design and selection of chillers, parameters include performance, efficiency, maintenance, and product life cycle and environmental impact. In this study, a 200 liters batch size of the chiller was selected as this much quantity was easily available at various farms near the study area in Faisalabad. The size of chilling tank is 970 x 770 x 550 mm and frame dimension is 510 x1580 mm. An agitator motor of 186 W is installed for stirring action during process and an observation hole is provided for the inspection during data acquisition. The whole chiller unit is fabricated of stainless-steel material as shown in Figure 4.1.

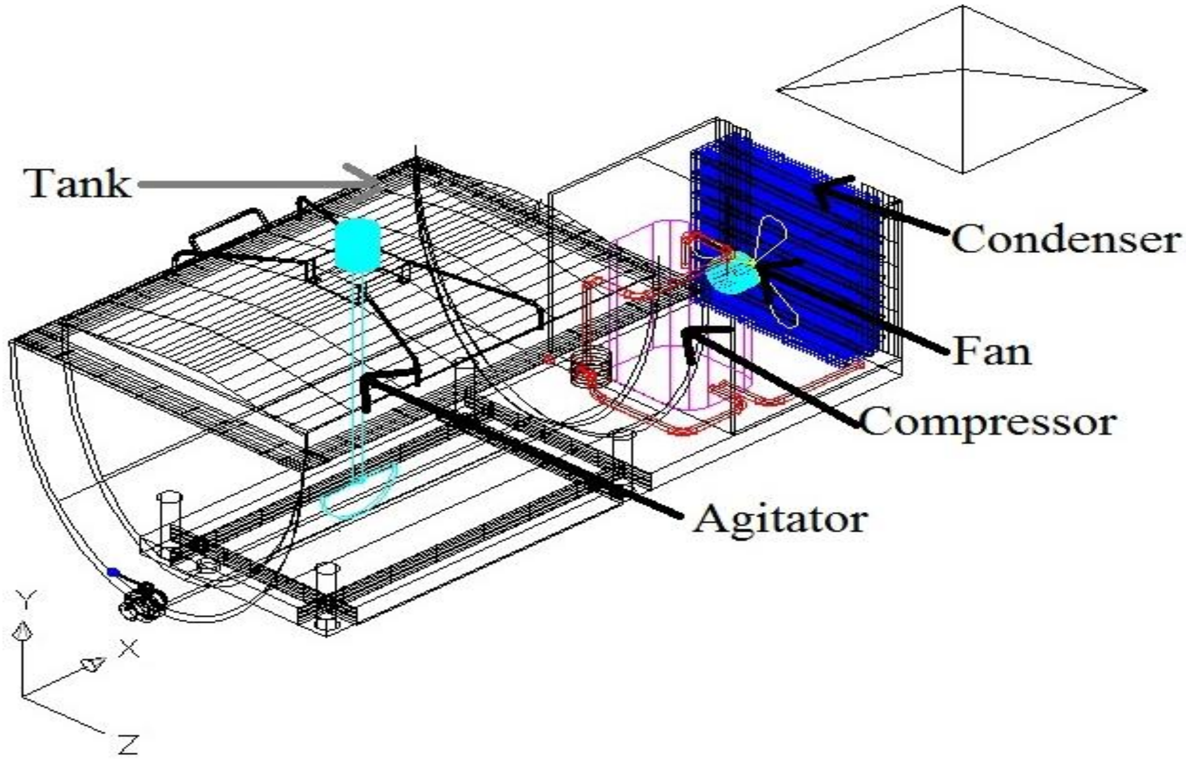

Figure 4.1: Schematic of milk chiller for the chilling process

The capacity of refrigeration (C_R) system in Tonnes of Refrigeration (TR) was calculated by using following formula

$$C_R = \frac{m\ c_p\ (T_i - T_f)}{3.5\ t} \qquad (4.1)$$

Where 'm' is the mass of milk in kg, 'c_p' is the specific heat of milk in kJ kg^{-1} K^{-1} and 'T_i' is the initial temperature of milk in the chiller to be processed and 'T_f' is the final temperature required for the preservation of milk inside the chiller and 't' is the time required in seconds to cool the milk from T_f to T_i and 3.5 is the conversion factor and is equal to 3.5 kJ s^{-1} per TR.

The initial temperature of milk (T_i) was taken as 30°C; (which is the average temperature which has to be maintained in the pasteurizer during the first phase of cooling prior to shifting to milk chiller). According to International Standards of WHO, it is to be cooled to the preservation temperature of 4°C in two hours (120 minutes or 7200 seconds). Keeping in view time losses during chilling and packaging etc., the system designed for 100 minutes (6000 s) time for a batch of 200 liters. The average value of specific heat of milk to be processed was taken as 3.89 kJ kg^{-1} K^{-1}. By substituting these values in Eq. (1), the tonnes of refrigeration (TR) was calculated to be 0.96 TR. Keeping in view 4-5% electro-mechanical losses, the actual capacity was selected as one tonne of refrigeration.

The coefficient of performance of milk chiller was calculated by using following formula:

$$\mathrm{COP} = \frac{\mathrm{Q}'}{\mathrm{P}} \tag{4.2}$$

Where Q′ is the amount of heat energy extracted from milk per unit time and P is the power supplied to run the refrigeration machine. Q' can be calculated by the following formula:

$$Q' = \frac{m\, c_p\, (T_i - T_f)}{t} \tag{4.3}$$

By substituting these values in equation (3), the rate of heat energy extracted (Q') was calculated to be 3.37 kJs^{-1} or 3.37 kW. While W' is the average power and was recorded by employing data acquisition bench as shown in Figure 4.2.

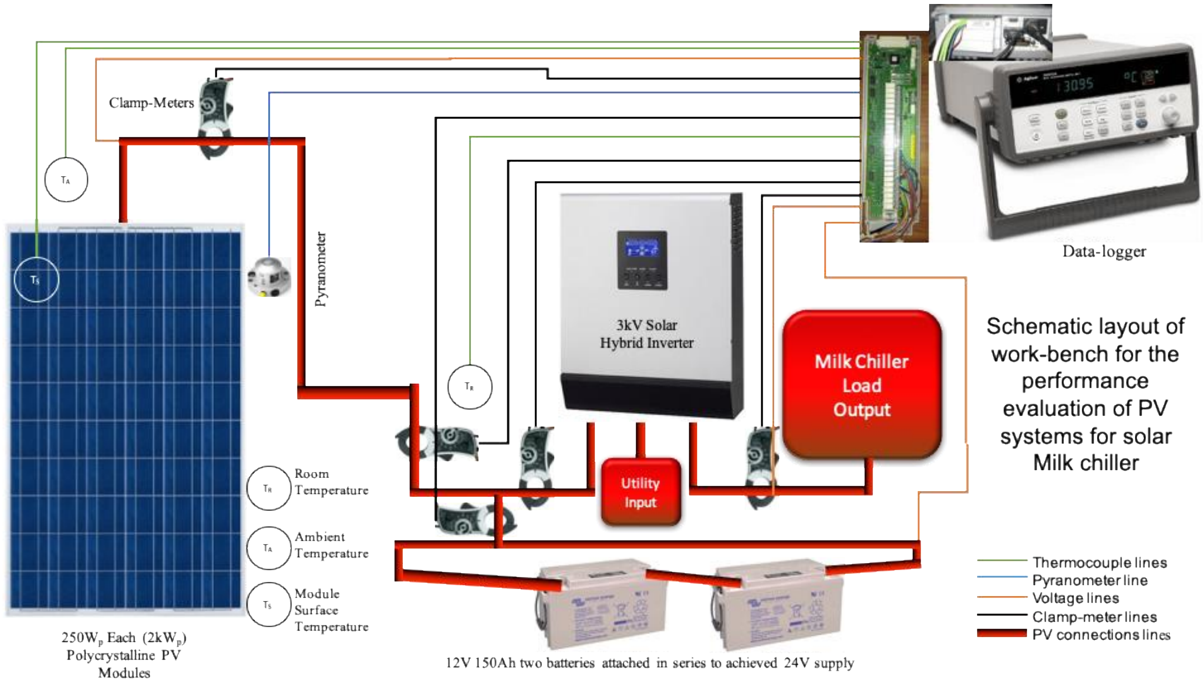

Figure 4.2: Data acquisition bench for solar milk chiller

4.4.2 Design of solar system for milk chiller

The solar system comprises solar PV array, inverter and battery bank for the solar milk chiller system. In this study, the size of solar system for a specific milk batch size was selected and same algorithm can be used for any size of the milk chiller unit. Peak power of solar system (P_p) in kW_p for solar milk chiller is calculated using Equation 4.

$$P_{peak} = \frac{P_c\, t\, Ip}{H_{avg}\eta_{Inv}\eta_{bat}T_{CF}} \qquad (4.4)$$

Where *'P_c' is the p*ower of compressor of the chiller, 't' is the time of operation of the chiller in hd^{-1}, I_p is the peak solar irradiance in kWm^{-2} and its peak value is taken as 1 kWm^{-2} for all calculation as a rated value, H_{avg} is the average Global Horizontal Irradiance (GHI) in $kWhm^{-2}d^{-1,}$ The average value of GHI in Faisalabad is lying from 5-6 $kWhm^{-2}d^{-1}$.

For calculation, its minimum value has been taken as 5 $kWhm^{-2}d^{-1}$, η_I efficiency of inverter in % and its value is lying in the range of 95-98%. However, its average value was taken as 96.50% for the calculation of peak power of solar PV system, $^{\eta}{}_b$ efficiency of battery in % and its value is lying in the range of 0.85-0.95. However, its average value is taken as 90%, T_{CF} temperature correction factor and its value is calculated by subtracting from unity the product of loss factor (0.4% per ^{o}C) and change in PV temperature at NOCT and STC conditions for crystalline Silicon. It means by increasing temperature from its optimum value (25°C) at Standard Testing conditions (STC), power reduces about 0.4% per degree increase in temperature from 25°C. By substituting all these values in Equation (4), the value of PV_{peak} was found to be 2 kW_p. Eight (8) number of poly crystalline PV panels having (250 W_p each) were used in the form of one string. The capacity of the inverter was calculated as 3 kW by taking surge factor as 2 which can easily accommodate the torque and running load for the compressor motor of one ton of refrigeration system; nevertheless, a VFD has been coupled with the compressor unit to minimize torque load.

In hybrid system, the solar system is also equipped with utility or grid supply, so battery backup is needed for a shorter period that is only available for the period when solar and electricity (utility) is not present so battery backup system was designed only for period of two hours which is sufficient to complete batch of 200 liters milk and that is calculated by using following formula

$$C_{bat} = \frac{P\ t_b}{D_d\ \eta_{bat}\, V_{bat}} \tag{4.5}$$

Where C_{bat} is battery capacity in Ah, D_d is depth of discharge in fraction, η_{Bat} is battery efficiency ranges from 0.90 to 0.98, V_{Bat} is nominal voltage of battery t_b is the minimum backup time in hours. By putting all he values in equation 5, the capacity of battery bank was calculated to be 292 Ah. Keeping in view the standard size of the batteries and its voltages, two 150 Ah batteries are used in series circuit to back up the solar milk system even in the absence of solar and utility energy supply. The hybrid solar PV system have more long life and less costly as compared to stand alone PV system because it requires less numbers of batteries as required in standalone system. The pictorial view of the installed system at Solar Campus, UAF is shown in Figure 4.3

Figure 4.3: Complete solar chiller unit installed at Solar Campus, UAF

4.4.3 Experimental setup

The experimental analysis was carried out with different milk batch sizes (50L, 100L, 150L and 200L) using reciprocating compressor, rotary compressor with capacitor and rotary compressor with inverter technology to optimize the operating conditions (power load, energy consumed). All the batch sizes were analyzed with the same starting conditions such as ambient temperature, sunshine hours, and no clouds. Each spell of milk was extensively observed to avoid any human error during the entire experiment for each batch size. Experiments were conducted with milk having approximately temperature of 30°C and the raw milk was transferred into the chiller to cool down it up to 4°C within 2 hours. A digital scale was also installed at the wall of chiller to record the quantity of milk in liters. An inspection hole of 220 mm diameter was provided at the right corner of the chiller on top cover gate and milk drain valve was provided at the right bottom side of the tank to supply the milk to the packaging machine.

4.5 Results and Discussion

4.5.1 Refrigeration system optimization

Since the chilling process is a sensitive process in term of chilling temperature and order to complete the process within specific time as indicated by WHO. Similarly, an idea about the energy consumption and power requirement is also necessary to investigate for the development of a relationship between quantities of milk to be processed. For this purpose, complete database was developed using a digital data logger, which was coupled with milk chiller (shown in Figure 4.2).

In the first phase of the research, a conventional reciprocating compressor was used with R22 refrigerant. The system performance was satisfactory in terms of meeting the temperature requirement of the milk from ambient temperature 30°C to 4°C which is the requirement of WHO. The major drawback was the high initial torque load (3.7kW) which was not feasible and economical to couple with solar PV system for decentralized applications. The overall average load was recorded was above 1.5 kW as shown in the Figure 4.4. The figure also shows that the time required to achieve a temperature of 4°C was found to be 72 min.

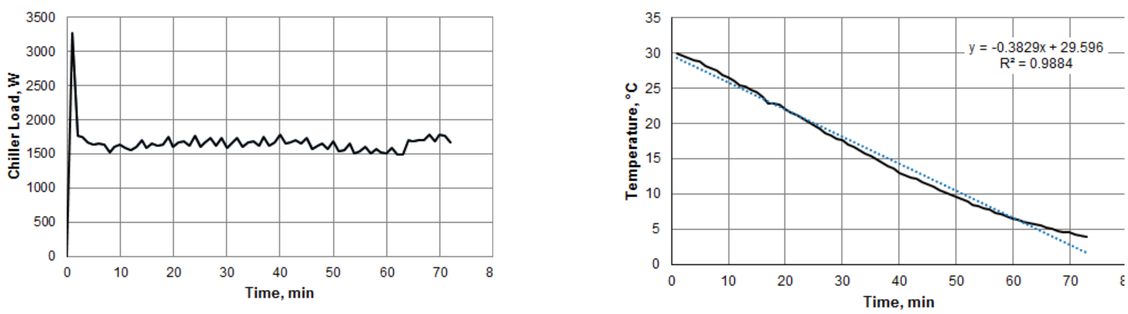

Figure 4.4: Load and temperature variation during chilling process (Conventional reciprocating compressor, Refrigerant: R22)

In the second phase of this research the rotary type compressor was installed by using environment friendly R-410 refrigerant in the same vapor compression refrigeration system. This system was equipped with two conventional type capacitors; one for starting the capacitor and other for running the compressor continuously. The data recoded with this type of technology was quite satisfactory, however the torque load was still recorded to be as almost 1.7 kW and running load was recorded to be greater than above 1.2 kW. This was an acceptable solution but still running such system on PV can reduce the performance of the system and heavy amount of backup system is needed to run such type of systems as shown in Figure 4.5. The Figure also shows that the time required to bring milk temperature to 4°C was recorded to be 72 min.

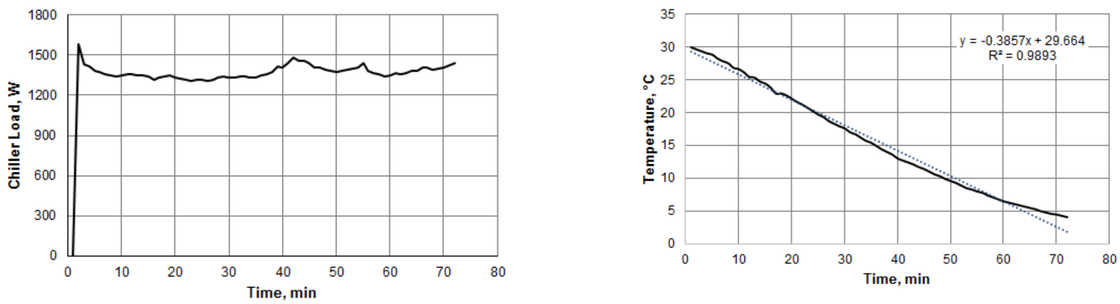

Figure 4.5. Load and temperature variation during chilling process (Rotary compressor, Refrigerant: R410)

The third and successful phase of this research was conducted to optimize the system to run perfectly with hybrid solar PV system. To reduce the torque load of the chiller, an inverter technology was used which successfully eliminated the torque load as well as the running load of the chiller was also reduced up to 20%. The overall average load was recorded below 1 kW which is 45% less than the first phase of the research as shown in the Figure 4.6. The results show that a temperature of 4°C was achieved within a time period of 100 min which is within the standards of WHO. There was a linear relation of temperature versus time in all the cases as determined by regression analysis (R^2= 0.95).

This optimized system can run smoothly and efficiently with only less than 1 kW of load without compromising on COP of the system.

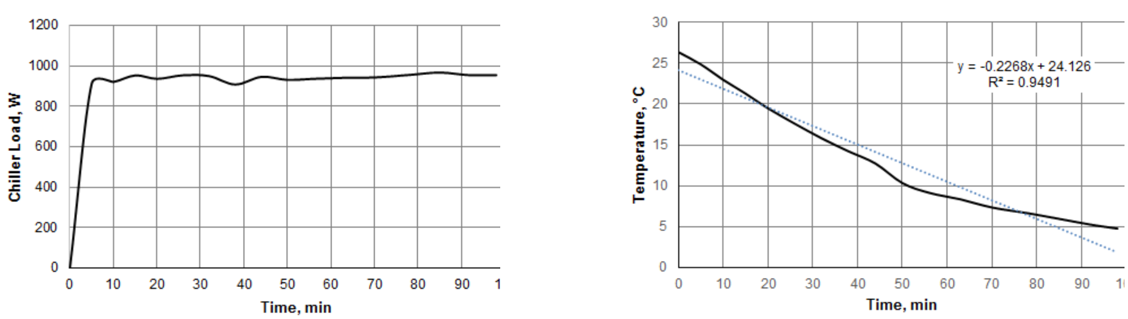

Figure 4.6. Load and temperature variation during chilling process (Rotary compressor with inverter technology, Refrigerant: R410)

Consecutive series of trials on equal amount of milk provided by University Dairy Farms were carried out and following observations were recorded as given in the following. The overall average torque load was recoded below 1 kW which is 45% less than the first phase of the research (reciprocating type) as shown in the Figure 4.7.

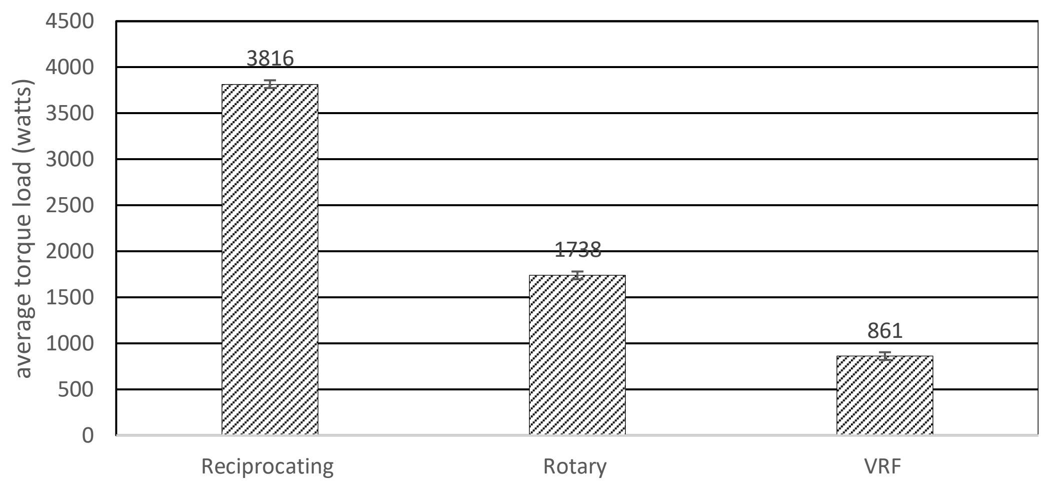

Figure 4.7: Comparison of average torque (maximum) load for different type of compressors

Whereas Figure. 4.8 shows one of the results taken using 200 liters milk with VRF technology. In inverter technology, there is no torque load and system started from zero. In the middle range of experiment when the process progresses, the compressor runs at its rated capacity to extract heat continuously from heated milk but as soon as milk temperature approached the storage temperature, the power consumption by the compressor again became slow as indicated by the curve.

As the compressor has to extract heat energy from the milk supplied under the ambient condition. It is evident from the figure that at the start of chilling process, less energy was consumed because some of the energy was taken by the vessel of chilling chamber. The variation in energy used pattern was due to the transient heat transfer at the start and rate of cooling became uniform in the middle range once the steady state conditions achieved.

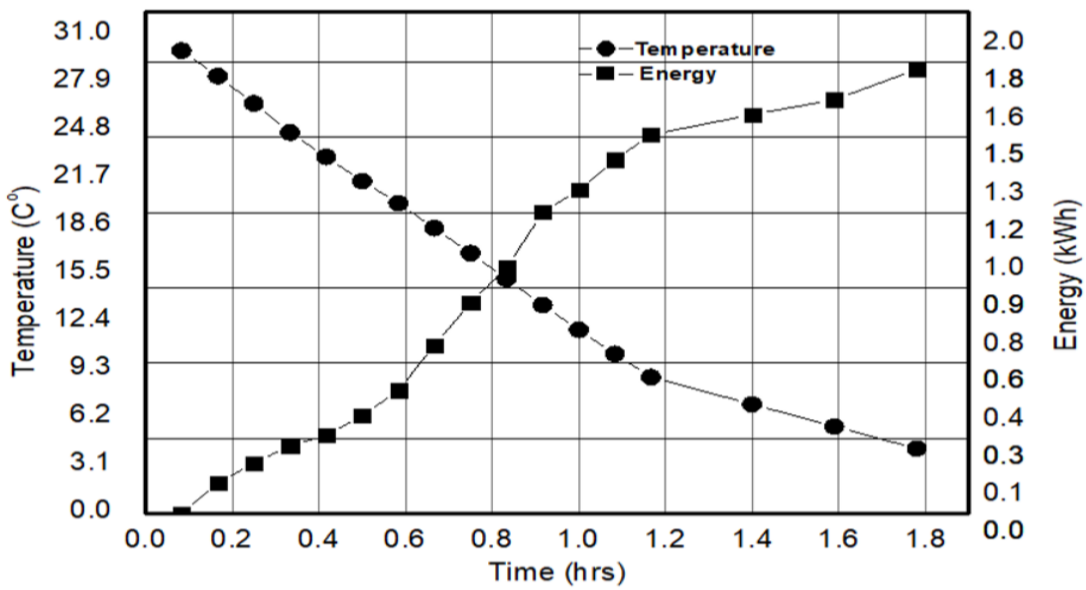

Figure 4.8: Load and temperature variation during chilling process of 200 liters milk (Rotary compressor with inverter, Refrigerant: R410)

To optimize the energy requirement and chilling time, different batches were processed using rotary compressor with inverter technology (VRF) as shown in Figure 4.9. It showed that processing at full capacity (200 liters) and the best fitted model was found to be second order polynomial with high value of coefficient of determination for both values of energy used and chilling time. The results have shown that by increasing batch size from 50 liters to 200 liters, rate of energy used was low comparative to rate of energy usage at low batch sizes. Similar trend was found in case of chilling time. It shows that milk processing at full capacity batch is economical in terms of chilling and energy consumption. In case of processing small batch sizes, the rate of energy usages is more due to less exposure of cooling coils with milk, so cooling losses take place due to unutilized contact area of the cooling coils. Nevertheless, there was no effect on the quality of processed milk if the batch size was reduced from the rated capacity of the chiller but there is litter compromise on chilling time and energy per unit weight of the processed milk. It also shows that any size of the batch can be processed at the farm level.

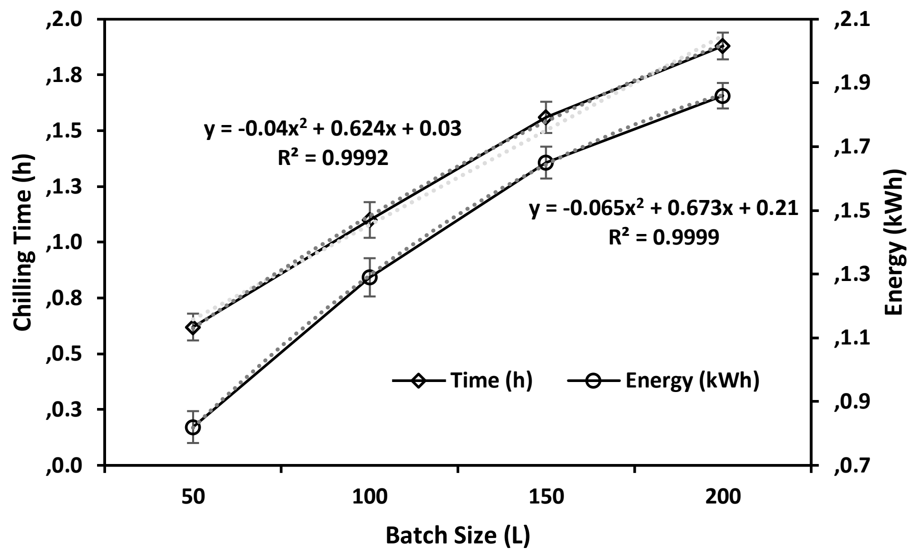

Figure 4.9. Energy used and chilling time variation under different batch sizes (Rotary compressor with inverter technology, Refrigerant: R410)

4.5.2. Compressor type optimization

Similar experiments were replicated using all three types of compressor (reciprocating, rotary, rotary with inverter) to show a comparative overview of chilling time and energy use as shown in Table 4.1. It can be observed that milk processing using a rotary compressor with inverter technology gave significant outcomes showing the use of this technology is better over the conventional ones in term of performance and energy saving. Vapor compression refrigeration system was used with VRF kit to reduce the load.

Table 4.1: Comparison of compressor types under various batch sizes

Batch size	Compressor type	Chilling time (h)	Energy used (kWh)	Standard errors	C.V. (%)	P-value
50L	Reciprocating	0.39	1.15			
	Rotary	0.41	0.91	0.014	1.64	< 0.0001*
	Rotary with inverter	0.62	0.82			
100L	Reciprocating	0.75	1.65			
	Rotary	0.82	1.38	0.011	0.78	< 0.0001*
	Rotary with inverter	1.10	1.29			
150L	Reciprocating	1.15	1.92			
	Rotary	1.31	1.67	0.019	1.26	< 0.0001*
	Rotary with inverter	1.58	1.65			
200L	Reciprocating	1.17	2.4			
	Rotary	1.86	1.92	0.012	0.86	< 0.0001*

*P-value ≤ 0.001 (significant); **P-value≥ 0.001 (insignificant)

R410a refrigerant was used in the compression and the flow rate of the refrigerant was used as 1.4 L/min having specific volume as 0.0009 m^3kg^{-1} (m′=1.55 kg/min). The refrigerant was found in superheated phase before and after isentropic (constant entropy) compression process and condensation process was found to be isobaric and there was no sub-cooling. The expansion process through capillary tube was irreversible adiabatic (constant enthalpy) and the milk heat was absorbed in the evaporator coils at constant pressure. The temperature, pressure and enthalpy variation in compressor, condenser, capillary tube and evaporator have been shown on Temperature-Entropy (T-s) and pressure-enthalpy (p-h) diagrams in Figure 4.10.

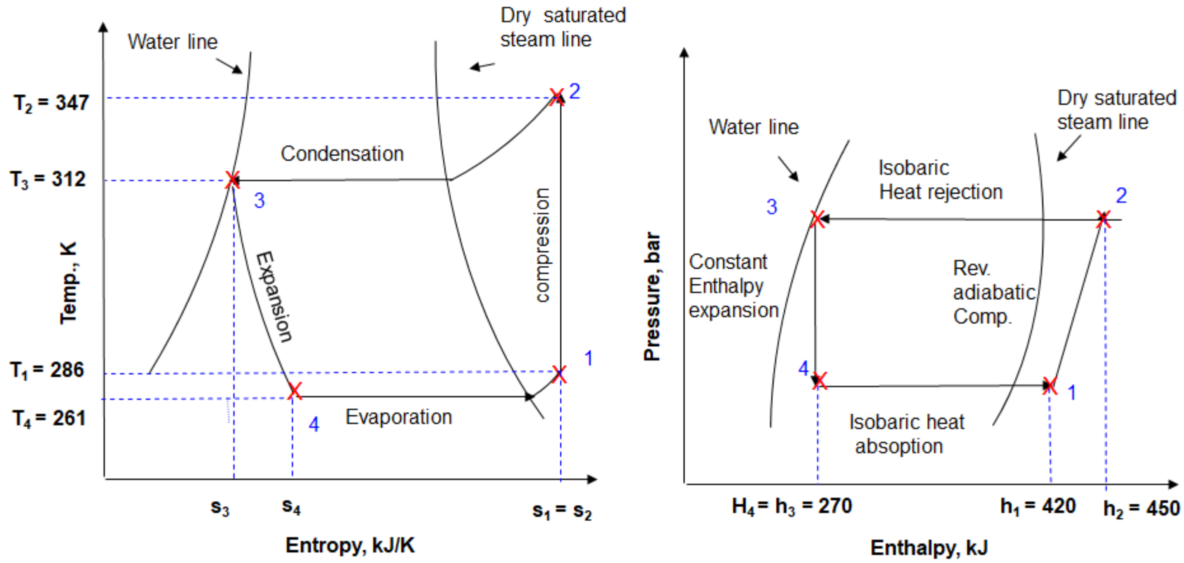

Figure 4.10: Temperature-Entropy (T-s) and pressure-enthalpy (p-h) diagrams of the optimized compressor of the solar chiller system

The rate of heat absorbed by the refrigerant in the evaporator (*Q′*) in kW is calculated by the following formula

$$Q' = m'(h_{1-}h_4) \qquad (4.7)$$

Where m’ is the mass flowrate of the refrigerant, h_1 and h_4 are the enthalpies at the evaporator outlet and inlet respectively. The rate of heat extracted was calculated to be 3.88 kW and tonnes of refrigeration (TR) were calculated to be 1.11 (3.88/3.5).

Theoretical Power is calculated by the following formula

$$P = m'(h_{2-}h_1) \qquad (4.8)$$

Where h_1 and h_2 are the enthalpies at the compressor inlet and outlet respectively and the theoretical power was calculated to be 0.77 kW. Actual power of the system was recorded by the data logger and found to be 0.96 kW and 0.19 KW (≈ 20%) were the thermal (cooling) losses of the milk chilling system.

COP of the system was calculated by dividing rate of heat absorbed (Q′) by actual power (P) and is calculated to be 4.

The average values of COPs thus calculated were found to be 0.8831, 1.939 and 3.918 for conventional reciprocating type compressor, rotary type compressor with capacitor technology and VRF technology respectively. The results have shown that it is best to use solar energy along with variable refrigerant flow (VRF) or inverter type technology for milk processing in terms of energy efficiency. This comparison revealed that coupling of these technologies with solar energy not only reduce the power requirement but also to reduce the size of the PV system coupled with this system. So, it is evident that there is significant difference of the power required by using VRF technology and it provides best opportunity to use the PV system to operate the unit. This VRF technology has not only reduced the power requirement but also eliminate the torque load required to start the compressor.

4.6 Conclusion

Milk processing in rural areas needs efficient decentralized renewable energy solutions not only for handling the fresh milk at farm level but also providing a cheaper sustainable solution to small entrepreneur. In this study, a detailed thermal analysis has been carried out of a milk pasteurization system coupled with Scheffler fixed focus concentrator and evacuated tube collector to investigate the useful energy and losses during the process of milk pasteurization. The available energy was estimated to be 8.10 and 5.63 kWh at the aperture areas of SC and ETC, respectively. Under the constant range of solar radiations (GHI), the pasteurization process is quite smooth with gradual increase in temperature and process completed in 80-90 minutes to reach a temperature of 63°C from ambient temperature. The total power consumed was recorded to be 2.67 kW to reach this pasteurization temperature. The total energy required for the pasteurization of 100L batch of milk is 3.57 kWh. Though results showed that solar milk pasteurization can be successfully done using SC yet under the average beam radiation range of 686 Wm-2, the overall efficiency of the system was found to be 58%. On the other side, in case of ETC, the overall efficiency of the system was found to be 74%. These results are in accordance with results obtained from predicted values (54% for SC and 71% for ETC) showing the reliability of the developed algorithm. Research concluded that both systems can be effectively used for the milk pasteurization system, however, the system coupled with ETC is more efficient, simple in design and provides thermal storage to continue the process under varying weather conditions.

Acknowledgment

The authors gratefully acknowledge the International center for decent work and development (ICDD) University of Kassel Germany for funding of this project. We would also like to appreciate Deutscher Akademischer Austauschdienst (DAAD) and Fachgebiet Agrartechnik Uni Kassel Witzenhausen (AGT) for their cooperation and support during pre and post research activities for the present study. Finally, we would like to acknowledge Department of Energy Systems Engineering, University of Agriculture Faisalabad Pakistan (ESE-UAF) for providing technical assistance and site place for the development and installation of systems used for the project.

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5. Improving milk value chains: A case study for qualitative-economic feasibility of decentralized solar milk pasteurization and chilling processes

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Abstract

Milk adulteration is very common during processing and in whole supply chain, particularly in least developed countries (LDCs) like Pakistan. The dairy farmers have to sell raw milk due to inadequate farm-gate milk processing facilities leading to economic and quality compromises for producers and consumers respectfully. The current study has been taken up to investigate the milk quality processed with indigenously developed Solar Milk Chiller (SMC) and Solar Milk Pasteurizer (SMP) coupled with an evacuated solar tube collector in comparison with existing milk value chain and techno-economic feasibility of these developed technologies. The quality attributes like fat (5.4%), solid-not-fat (9.1%), salts (0.7%), protein (3.9%), lactose (4.2%), total solids (14.5%), pH (6.85), density (1.031 kg/l) and freezing point (-0.532°C) of processed milk were found within the standardized ranges. The results of sensory evaluation using a 9-point hedonic scale showed overall likeness towards solar processed milk in terms of taste, color, aroma, and freshness. With an estimated operational lifespan of 10 years, the payback periods for SMC and SMP have been found to be 1.3 to 4.5 and 1.1 to 2.7 years respectively, depending upon the alternate source for equivalent energy generation. The processing cost per liter of milk, both for chilling and pasteurization, was calculated to be 0.003 USD with these solar powered technologies.

Keywords: Solar milk chiller, Solar milk pasteurizer, On-farm milk processing, Milk adulteration.

5.1. Introduction

Pakistan is the world's fourth largest milk producing country following United States, Russia, and India (Rehman et al., 2017), but unfortunately, milk quality is depreciated by various chemical and microbial adulterants during processing and in whole supply chain

(Khan et al., 1999; Faraz et al., 2013; Barham, 2015a, b; Akhtar et al., 2015; Ahmad et al., 2016). The milk production and distribution systems in the developing countries are still very traditional and strongly dominated mainly by the informal private sectors, consisting of various agents, i.e., producers, collectors, middlemen, processors, traders, and dairy shops with each performing a specialized role at a particular point in the supply chain (Zia, 2006). Furthermore, the lack of quality assessment is the most neglected aspect of the whole system. There is almost no testing at any stage along the marketing chain (Awan et al., 2014). Majority of milk shops in urban areas are exposed to dust and flies and very few among them have a refrigeration facility. The containers used in transportation are unhygienic, and milk adulteration is another serious concern in the peri-urban milk supply chain. On the other side most consumers in Pakistan are price conscious, so demand for open raw milk is high as compared to processed milk (Jalil et al., 2009). The extensive consumption of milk and dairy products makes these foodstuffs targets for potential adulteration with financial gains for unscrupulous producers (Nicolaou et al., 2011). Milk suppliers upturn their profit from the sale of milk through dilution, extraction of valuable components (i.e., cream), and/or use of additives to enhance the total solid content. Hence, the milk for consumption has been adulterated to such an extent that there is very little nutritive value left in it (Lateef et al., 2009).

The simplest and oldest form of adulterant in milk is water to increase the volume for profitable commodity (Bhatt et al., 2008), but contaminated water has a potential risk to human health regarding waterborne diseases (Campos Motta et al., 2014). When water is added to milk, its foamy appearance diminishes. To give milk its foamy appearance, artificial detergents are commonly added (Lateef et al., 2009). Middlemen usually attempt to counter the dilution by adding cane sugar to extend the solid content of the milk. They also add additives like starch to mask the effect of dilution by water and to increase the viscosity of milk up to the consumer acceptance level (Afzal et al., 2011). For whiteness and genuine appearance, potassium and calcium salts of thioglycolic acids can also be added (Soomro et al., 2014). Milk is also adulterated illegitimately with formaldehyde, melamine, urea, and sugars for preservation, protein content enhancement, and taste improvement, respectively (Ahmad et al., 2016). On the other hand, microbial contamination of pasteurized milk can occur from different sources, such as dirty milking equipment, inefficient pasteurization, contamination from the environment, poor packaging, unsatisfactory sanitation, and unsuitable storage temperature or a combination of these (Fulya, 2011). Milk is transported to peri-urban and urban areas at ambient temperature from far-off places distancing up to 100 km, thus contaminated bacteria might get multiplied and attain a high number during this transportation. These high counts are linked with unhygienic milk handling, contamination from animal bedding, mixing of normal milk with the milk collected from the animal suffering from streptococcus uberis induced mastitis, etc. (Muhammad et al., 2009).

Owing to inadequacy of on-farm processing facilities, the dairy farmers must sell high-quality perishable milk to milkmen and large milk collectors on traditional system (Lateef et al., 2009), thus missing processing incentives ranging from USD 0.0125 to 0.0375/liter (FAO, 2011). About 95% of the milk in Pakistan is marketed raw through informal marketing chains, providing opportunities to unscrupulous persons at every step of milk value chain for adulteration, ultimately resulting in poor quality milk at consumer level (Javaid et al., 2009). Processors often purchase milk based on traditional quality criteria, such as smelling or boiling the milk to detect any curdling or adulteration. Processing operations are often carried out under unhygienic conditions. Costs in the informal milk processing industry depend on the sophistication of operations and the type of products produced. Generally, production costs include manual labor, premises rent, and fuel, ranging from fuel wood to electricity. For instance, a farm cooling tank of 200-litre capacity costs USD 3313, and one of 1000L capacity USD 6812, thus, conventionally milk is stored in basic, non-food-grade containers using ice (may be contaminated) as refrigerant to avoid spoiling, especially in the summer season (Awan et al., 2014). In summary, high procurement and operational costs are the main factors which limit the dairy farmers to install chilling units and pasteurizers for on-farm dairy processing.

The dairy farms having milk processing facilities, large proportion of expenditures account for providing fossil-fuel based energy inputs for continuous operation. The dairy sector alone emits about 4% of total anthropogenic greenhouse gases (GHGs) equivalent to around 1.2 billion tons of CO_2 per year (FAO, 2010). The immense use of fossil fuels as primary energy source in dairy processing is contributing to environmental pollution which needs serious attentions to shift the dairy processing on renewable energy resources (Shine et al., 2020). Pakistan receives immense solar energy, 19 MJm^{-2} for 7.6 hours a day with an average DNI ranging between 5 to 7 kWh m^{-2} d^{-1} (Ghafoor et al., 2016). There are more than one billion (56%) people living in rural and far-flung areas of Pakistan and mostly relying on wood, charcoal, dung cakes, crop residue or carbon-based fuels to fulfill their energy needs. Whilst around 0.51 billion (27%) of them are still not connected to the national electricity grid and the remaining even if connected, the transmission lines are only limited to the populated areas for household use only while most of the dairy farm operations are performed away from villages (REN21, 2017). In a nutshell, there is a strong need of devising self-sufficient, viable and off-grid energy solutions to the rural areas where more than 60% of the country's population lives (GOP, 2016). Residing the fact, country's massive solar potential can be utilized to meet the energy demand particularly at dairy farm level in a decentralized manner. The promotion of innovative solar based technologies for dairy processing can scale up the on-site facilities which will not only provide an excellent opportunity for on-farm dairy processing of perishable milk but also contribute towards sustainable rural development.

Acknowledging all the facts stated above, the present research deals with the processing quality and techno-economic evaluation of indigenously developed solar based milk processing technologies viz. Solar Milk Chiller (Khan et al., 2020) and Solar Milk Pasteurizer (Khan et al., 2021). The quality of vendor sold raw milk, milkmen supplied milk, company processed milk and solar processed milk have also been investigated in the study by examining the physical attributes: water added (W, %), freezing point (Fp, °C), temperature (T, °C), density (D, kg/l) and pH, and chemical attributes: fat (F, %), protein (P, %), salts (S, %), and solids-not-fat (SNF%) and lactose (L, %). The comparative results of milk quality revealed that the solar processed milk has better quality than all other analysed samples with nominal processing charges of 0.003 USD for chilling and 0.003 USD for pasteurizing per liter of milk.

5.2. Methodology

5.2.1 Experimental Layout and Data Collection:

The research has been conducted in the vicinity of Faisalabad, Pakistan including urban and rural areas to analyse the quality of vendor sold open milk, traditional milkmen supply, and company processed packed milk for making a comprehensive quality comparison with solar processed milk. An ultrasonic milk analyzer (Master Pro P1, Milkotester Ltd.) has been used in the study which has the provision to determine the different physical attributes: water added (W, %), freezing point (Fp, °C), temperature (T, °C), density (D, kg/l) and pH, and chemical attributes: fat (F, %), protein (P, %), salts (S, %), solids-not-fat (SNF%) and lactose (L, %) with a testing capacity of 50 samples per hour. The milk quality of randomly selected open milk selling shops in urban area (50) and peri-urban area (50), home delivering milkmen (50) and processed milk (05) has been tested with milk analyzer. Then, the acquired data was compared with the quality of milk processed with SMC and SMP. All the data was taken in triplicate and statistically analyzed using IBM SPSS Statistics 24® software. Consumer acceptability of solar processed milk has been evaluated on the basis of sensory evaluation using a 9-point hedonic scale anchored with like extremely to dislike extremely. The flowchart of research methodology is shown in the Fig. 5.1.

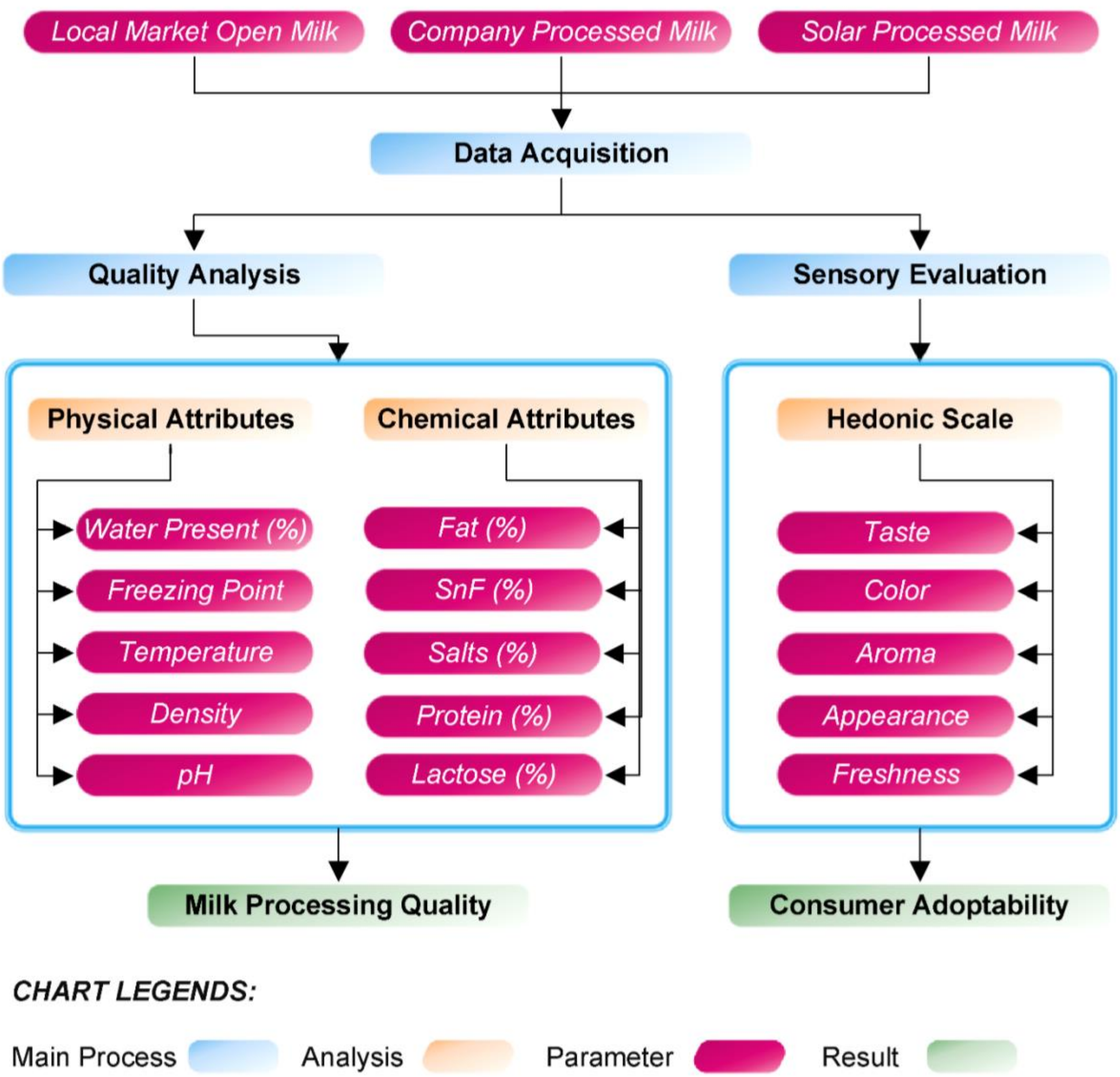

Figure 5.1: Flowchart of research methodology

After quality analysis, economic viability of developed SMC and SMP was investigated using straight-line method and per liter milk processing cost. Furthermore, carbon emission savings has also been estimated during the entire lifespan of SMC and SMP.

5.2.2 Quality Analysis

The quality of milk was examined with an ultrasonic milk analyzer (Master Pro P1, Milkotester Ltd.). For ensuring the accuracy and reliability of results, the milk analyzer was calibrated for local herd according to the standard procedures given in the company manual in the National Institute of Food Science & Technology (NIFSAT), University of Agriculture Faisalabad (UAF), Pakistan (Milkotester, 2021). The milk samples for their general appearance including dirt presence, odor (mild and cowey), color (yellow and bloody), texture (thin or watery), and sedimentation were physically observed according to the protocols stated by Khan et al., (2005). Although different physio-chemical parameters including W, Fp, T, D, pH, F, P, S, SNF and L were evaluated with ultrasonic milk analyzer, but for calibration purpose, lab testing has also been done. Milk fat was determined by Gerber method as described by Pearson (1976) and protein was determined by Kjeldahl method as reported by AOAC (2000). Total solids (TS, %) was evaluated by performing the standard procedure given by AOAC (2000) and using the following formula:

$$TS\ (\%)\ = \frac{Weight\ of\ dried\ sample}{Weight\ of\ milk\ sample} \times 100 \tag{5.1}$$

Harding (1995) reported the following equation to determine the SNF content present in a given milk sample:

$$SNF\ (\%)\ =\ TS\ (\%) - F\ (\%) \tag{5.2}$$

The lactose content of milk sample was investigated by the following formula (Javaid et al., 2009):

$$Lactose\ (\%)\ =\ TS\ (\%) - (F\% + P\% + Ash\%) \tag{5.3}$$

The ash contents (%) were examined by Gravimetric method using Muffle furnace at 550°C, as reported by AOAC (2000). Hygienic status of milk was measured by using Methylene Blue Reduction Test (A.O.A.C., 1997). Various milk adulterants like water, starch, urea, formalin, hydrogen peroxide, detergents, oil and cane sugar were detected by using standard procedures (Tipu et al., 2007). The samples of milk processed with SMC and SMP were investigated for sensory characteristics viz. taste, color, aroma, appearance, and freshness on a 9-point hedonic scale (0–9) according to the procedure described by Chapman, (2010).

5.2.3 Statistical Analysis

All the data was taken in triplicate and statistically analyzed using MINITAB (2000) software employing Fisher's analysis of variance technique. Least significant difference (LSD) test at 0.05 probability levels was used to compare the differences among the treatment's means (Steel et al., 1997).

5.2.4 Economic Analysis

Along with technical soundness, economic viability is also an important parameter for successful adoption of the developed technology among milk producers and processors. Therefore, developed SMC (Khan et al., 2020) and SMP (Khan et al., 2021) have been economically evaluated based on their payback period and revenue generated during their useful lifespans, using straight-line method (Raza et al., 2019).

The expenses comprised fixed cost including initial investment, depreciation (Eq. 4), interest (Eq. 5), insurance (2%), taxes (1.5%) and housing costs, and operational cost including labor, running (10%), and repair and maintenance charges (25%). Out of these expenses, the housing and labor expenses were not considered with the scope that the milk producers would process the milk with developed technologies at farm level by themselves.

$$Depriciation = \frac{Initial\ cost\ -\ Salvage\ value}{Years\ of\ useful\ life} \qquad (5.4)$$

The salvage value was taken 10% of the initial investment and expected life was assumed to be 10 years. Annual interest rate in Pakistan (7%) has been taken into account to calculate the interest with the following equation.

$$Interest\ = \frac{(Initial\ cost\ +\ salvage\ value) \times\ annual\ intrest\ rate}{2} \qquad (5.5)$$

The break-even analysis was performed to calculate payback periods. According to Munir et al., (2014), break-even point is the time required to equalize the total cost (fixed and operational) and revenue (in terms of cumulative fuel savings) and after this point, the developed machines starts to generate revenue in terms of fuel savings. All economic estimations have been carried out on hourly basis because weather conditions affect the daily useful working hours.

5.2.5 Carbon Emission Analysis

As the developed SMC (Khan et al., 2020) and SMP (Khan et al., 2021) are entirely solar based technologies, therefore zero carbon emission has been observed. A carbon saving analysis has been done to estimate the CO_2 emission in comparison with fossil-fuel based energy generating resources. For this purpose, the total energy utilized during the operational hours by developed technologies during their lifespans was calculated and after that, CO_2 emission was determined for non-renewable energy resources if they will be used to produce the equal amount of energy. The CO_2 emissions per kWh of energy generation using various fossil fuels have been reported by Quaschning (2010) which were taken into account for calculating the CO_2 emission caused by these fuels for equivalent energy generation.

5.3. Results and Discussion

5.3.1 Quality Analysis

5.3.2 Physical appearance

The results of physical appearance testing (Table 5.1) revealed that milk samples taken from vendor shops, milkmen and company milk had 53%, 19% and 1% dirty general appearance respectively. similarly, color appearance were found about 58%, 25% and 3% of the samples exhibited very mild while 13%, 4% and 0% had cowey odor; 15%, 6% and 0% samples with light yellow while 2%, 1% and 0% had bloody color for vendor shops, milkmen and company milk respectively. Samples were observed with 78%, 61% and 0% of thin texture along with 63%, 57% and 0% sediments for samples from vendor shops, milkmen, and company milk respectively. These results showed that the milk sold at vendor shops followed by milkmen were extensively put to the malpractices such as skimming and adulteration with water that probably carried out during the handling of milk starting from milking till it reached the shops/end consumers. It had bad color, odor, thin texture, and its general appearance was poor due to the dirt/sedimentation.

Table 5.1: ...... Physical appearance of milk samples tested from vendor shops, milkmen, company processed milk and solar processed milk.

Parameters	Property	Vendor Shops Milk	Milkmen Supplied Milk	Company Processed Milk	Solar Processed Milk
General appearance	Clear	47%	81%	99%	100%
	Dirty	53%	19%	1%	0%
Odor	Normal	29%	71%	97%	100%
	Very mild	58%	25%	3%	0%
	Cowey	13%	4%	0%	0%
Color	White	83%	93%	100%	100%
	Light yellow	15%	6%	0%	0%
	Bloody	2%	1%	0%	0%
Texture	Normal	22%	39%	100%	100%
	Thin/watery	78%	61%	0%	0%
Sediment	Absent	37%	43%	100%	100%
	Present	63%	57%	0%	0%

On the other hand, milk processed with solar based technologies i.e. SMC and SMP showed 100% clear appearance, white in color, normal in odor and texture with no presence of sediments, hence, showing better quality in comparison with other samples.

5.3.3 Physical attributes

pH: Mean pH value of milk samples obtained from other sources than the solar processed milk varied between 6.53 and 6.77 (Table 5.2) and was found within the normal range. Similar results were reported by different researchers (Memon, 2000; Inayat, 2002). The reason for lower pH value of market milk samples could be due to the addition of ice, water, or any other chemical preservative for extending the perishability of pure raw milk (Javaid et al., 2009). The highest and closest to the prescribed pH of the milk was of solar processed milk (6.85 $\pm$ 0.01) as it was pure and fresh without any contaminants.

Freezing point (Fp): The vendor sold milk had the highest freezing point range, varying significantly between -0.449 $\pm$ 0.19 and -0.463 $\pm$ 0.19, followed by company processed milk (-0.509 $\pm$ 0.04 to -0.528 $\pm$ 0.05) and solar processed milk (-0.532 $\pm$ 0.03). A number of factors including individuality, breed differences, developed acidity, colostrum, mastitis, stage of lactation, nutrition and season can affect freezing point of milk (Packard, 1995). Also, presence of mixed water in the local market milk can also be attributed to higher freezing point of the samples, as this fact has also been observed in the current study that the local market milk contained higher percentage of added water.

Table 5.2: ....Physical attributes of milk samples tested from vendor shops, milkmen, company processed milk and solar processed milk.

Milk Source		**pH**	**D (kg/l)**	**Fp**
Local Market Available Milk	Urban vendor shops	6.53 ± 0.01	1.028 ± 0.002	-0.449 ± 0.11
	Peri-urban vendor shops	6.68 ± 0.02	1.028 ± 0.001	-0.479 ± 0.09
	Milkmen Supplied Milk	6.60 ± 0.01	1.029 ± 0.001	-0.463 ± 0.19
Company Processed Milk	Haleeb	6.71 ± 0.01	1.031 ± 0.001	-0.518 ± 0.04
	Olper's	6.73 ± 0.01	1.030 ± 0.001	-0.523 ± 0.03
	Milk Pak	6.77 ± 0.01	1.030 ± 0.001	-0.528 ± 0.05
	Omung	6.62 ± 0.02	1.030 ± 0.001	-0.519 ± 0.04
	Gournmet	6.69 ± 0.01	1.029 ± 0.001	-0.509 ± 0.04
Solar Processed Milk (SMC and SMP)		6.85 ± 0.01	1.031 ± 0.001	-0.532 ± 0.03

Density (D): It has been observed that the local market available milk has the lowest density range (1.028 ± 0.002 to 1.029 ± 0.001), possibly again due to the dilution of water in raw milk (Javaid et al., 2009). Company processed milk (1.029 ± 0.001 to 1.031 ± 0.001) and solar processed milk (1.031 ± 0.001) were found more consistent with the standard density range of milk according to the Pakistan Pure Food Rule 1965 (Awan, 2000).

Temperature (T): The temperature of the samples during testing for vendor milk shops, milkmen and company processed milk ranged between 28.9°C to 30.3°C respectively with an average sample temperature of 29.2°C and were found within the testing conditions of the milk analyzer ((Milkotester, 2021).

5.3.4 Chemical attributes

The results of SMC and SMP processed milk are compared with local market available milk and company processed milk samples on the basis of different chemical attributes and represented in the Fig. 5.2

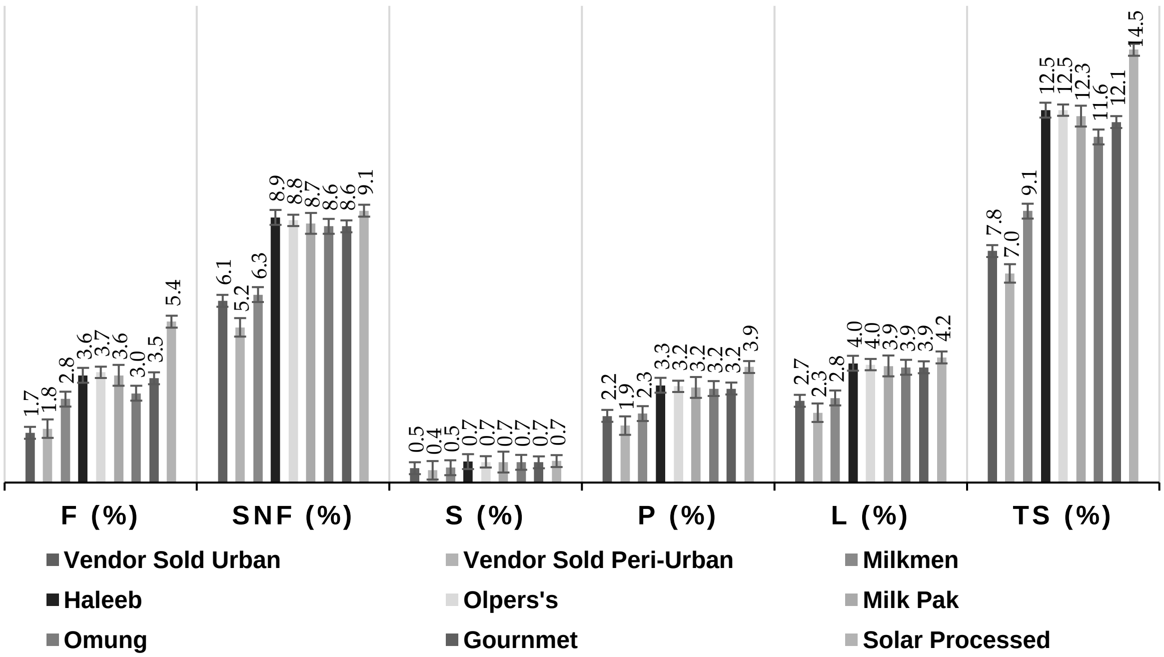

Figure 5.2: Comparison of chemical quality of SMC and SMP processed milk with existing milk supply chain

Fat (F): It can be observed from the Fig. 5.2 that the fat percentage of local market available milk varied between 1.7 and 2.8% and had the lowest values among all the other tested sources and likely to be the fat percentage of cow milk. The possible adulteration of cow milk or water might be the cause of these lower values of fat percentage. The same adulteration causes were described in the earlier studies (Prasad, 1997; Javaid el al., 2009). Skimming or partial skimming of milk is very common phenomenon in the local milk processing industries, thus resulting in decrease fat contents of the milk. Furthermore, the difference in breed, type and quality of feed, environmental conditions, and genetic variability can also be the causes of variable fat percent (Harding, 1995; Prasad, 1997). Meanwhile solar processed milk contained highest fat percentage (5.4%) which is close to standard and followed by the company processed milk in a range of 3.0 to 3.7% (Awan, 2000).

Solid-not-Fat (SNF): The SNF (%) of company processed milk have been found to be 8.6 to 8.9% and 9.1% for solar processed milk which resides within the prescribed standard of Pakistan Pure Food Rule 1965 (Awan, 2000). The results for local market milk SNF (%) did not fall within the legal minimum standard but found far much lower than that of cow milk (8.50%), as stated by Awan, (2000). These observations reside similar with the facts found in current study that local market milk samples were consistently adulterated with water or cow milk, as they exhibited higher freezing points.

Salts (S): Milk contains a variety of salts like phosphates, chlorides, carbonates and bicarbonates of sodium, potassium, calcium, and magnesium, etc. Overall concentration of salts was observed in the milk samples by milk analyzer and results revealed that salts were found in all the tested samples in a range of 0.5 to 0.7%. Lower salt percentages were found in vendor sold milk both in urban and peri-urban area while maximum salt percentage were observed in solar processed milk with SMC and SMP as can be seen in Fig. 5.2. The results were found consistent with those of Abd El-Salam and El-Shibiny (2011).

Protein (P): The highest protein (%) was observed in solar processed milk (3.9%), followed by company processed milk (3.2-3.3%) and local market process milk (1.9-2.3%) as shown in Fig. 5.2. The protein contents of solar processed milk and company processed milk have been found in line with the quality standards (Awan, 2000). However, variation in protein content (%) can be attributed to the quality of processing and managerial practices.

Lactose (L): Lactose (4.2%) was found highest in the solar processed milk and lowest in peri-urban area vendor milk (2.3%) as shown in Fig. 5.2. The lactose percent of company processed milk ranged from 3.9 to 4.0% while for local market milk, it ranged between 2.3% to 2.8%. Sharif, et al. (2007) reported a reduction of the lactose (%) in the Pakistani buffalo milk with the severity of sub-clinical mastitis, but for the current study, the most appropriate reason can be the adulteration of milk, resulting in lower lactose contents in local market milk.

Total solids (TS): Total solids content (%) of local market milk was averaged 7.96 ± 0.34% which were much lower than the average value of company processed milk 12.19

$\pm$ 0.27% and solar processed milk (14.5%) and also do not meet the quality standards (Awan, 2000). Overall, TS (%) for the local market milk and company processed milk ranged between 7.0 to 9.1% and 11.6 to 12.5% respectively. The most standardized TS (%) was observed in the solar processed milk followed by the company processed milk as shown in Fig. 5.2.

5.3.5 Milk hygiene status

The hygienic conditions of local market milk, company processed milk and solar processed have been observed comparatively for evaluating the quality of milk processing and results are represented graphically in Fig. 5.3. It is clear from the observations that overall, 52% of local market milk samples have been found in unhygienic status. Segregating the results by sources, 9% of vendor sold urban milk, 8% of vendor sold peri-urban milk, and 3% of milkmen milk samples decolorized the dye within the two hours; 25% of vendor sold urban milk, 19% of vendor sold peri-urban milk, and 17% of milkmen milk samples decolorized the dye in 2 to 6 hours; whereas 18% of vendor sold urban milk, 21% of vendor sold peri-urban milk, and 22% of milkmen milk samples decolorized the dye in 6 to 8 hours, representing the acute unhygienic conditions of milk provided by these milk sources as shown in Fig. 5.3.

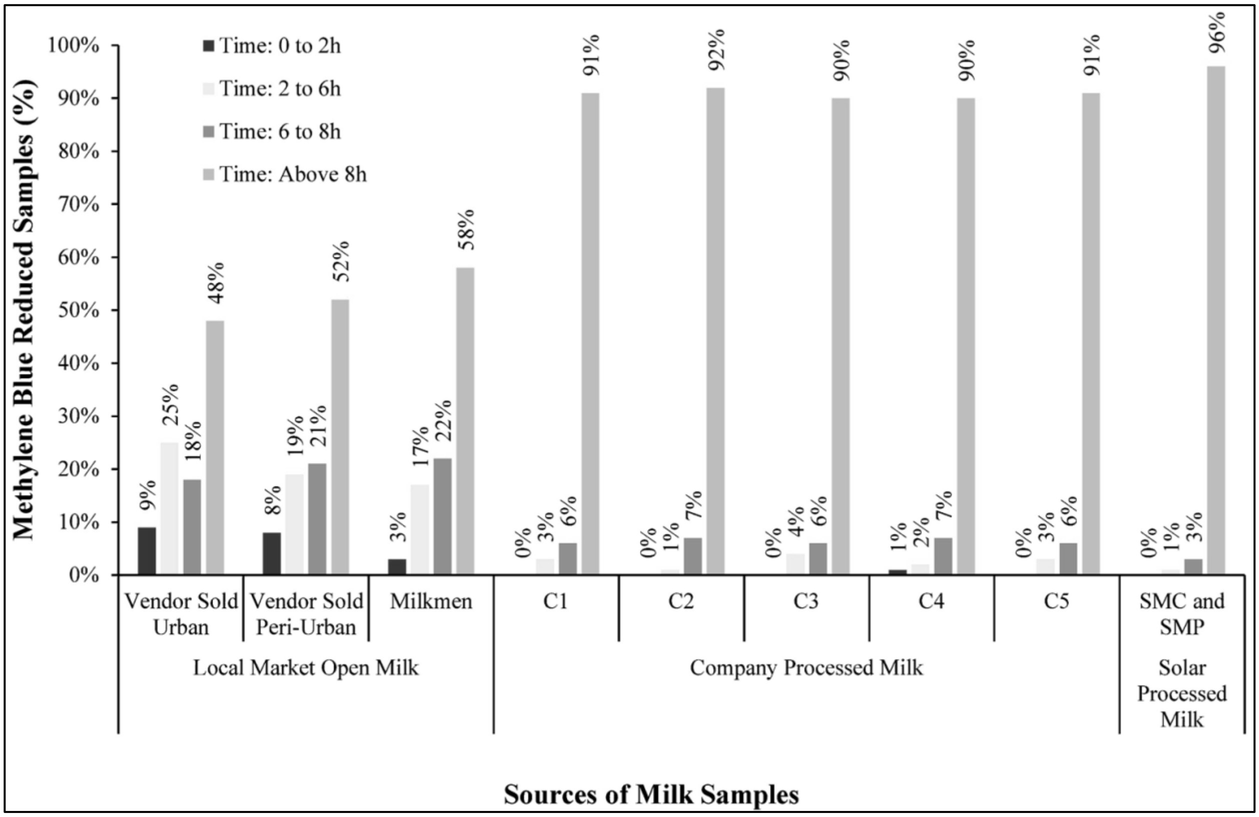

Figure 5.3: Hygienic grading of tested milk samples

The appropriate causes can be excessive and uncontrolled boiling of milk i.e., continuous boiling on low fire or presence of health hazard contaminants from water adulteration (Memon, 2000). The methylene blue reduction did not take place even after the end of 8 hours in solar processed samples, proving a 100% hygienic status.

5.3.6 Milk adulteration

Local market milk samples only were analysed for the adulteration in comparison with solar processed milk. The findings of determination of adulterants in local market milk and solar processed milk samples are represented in the Fig. 5.4. It is clear from the results that local market milk samples (urban vendor milk, peri-urban vendor milk and milkmen milk) were extensively adulterated with water (93, 89 and 71%), urea (66, 59 and 37%), formalin (31, 21 and 9%), and cane sugar (76, 81 and 57%) respectively. Only a minute fraction of starch (2%), H_2O_2 (2%) and detergents (1%) adulteration were found in urban sold milk samples. The solar processed milk was found adulteration-free in all aspects.

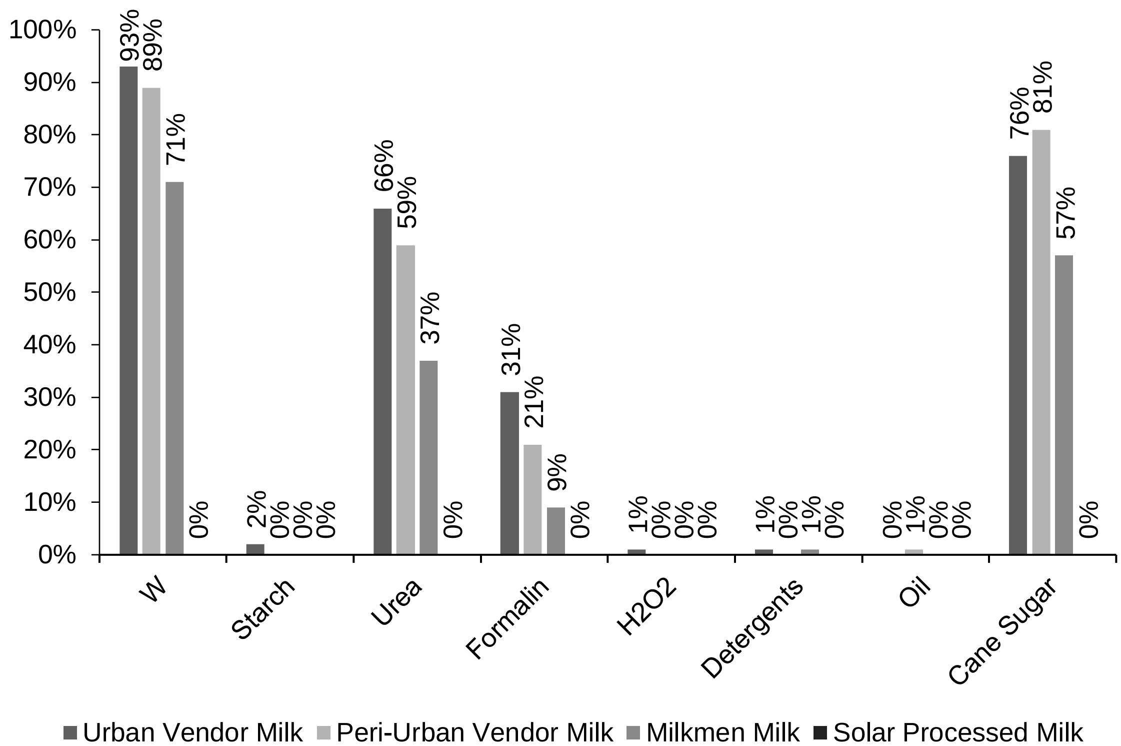

Figure 5.4: Milk adulteration in local market milk and solar processed milk

The adulteration malpractices by the unscrupulous persons in traditional milk supply chain are very common and have been reported by the many authors, therefore, the findings of the study are found to be consistent with them (Khan et al., 1991; Lateef et al., 2009; Awan et al., 2014; Barham et al., 2015a,b).

5.3.7 Sensory evaluation

The solar processed milk samples were evaluated for observing the overall acceptability of the milk. A panel of 20 evaluators selected from the experienced faculty members and postgraduate students reported the overall acceptability of milk. About 75% of the participants were agreed on the overall acceptability of solar processed milk on 'Like Extremely' scale. Overall likeness or dis-likeness based on 9-point hedonic scale evaluation is shown in the following Table 5.3.

Table 5.3: .... Sensory analysis for acceptability of solar processed milk

Dislike Extremely	Dislike Very Much	Dislike Moderately	Dislike Slightly	Neither Like or Dislike	Like Slightly	Like Moderately	Like Very Much	Like Extremely
0%	0%	0%	0%	5%	0%	10%	10%	75%

5.4 Economic Analysis

The economic feasibility of SMC and SMP was determined by performing a comprehensive economic analysis in terms of renewable energy generation from both sources, i.e., solar thermal using evacuated solar tube collector and PV. The capital costs of SMC and SMP were 2516 and 2201 USD respectively including all required accessories and installation charges. The available data for economic analysis is given in Table 5.4.

Table 5.4: .... Available data for economic analysis

Parameter	Value	Description
For SMC		
Total initial cost	2,516 USD	1 USD = 159 PKR
Expected Life of CSR	10 year	~ 44,000h @ 12 useful hd^{-1}
Salvage value	10%	of initial cost
Interest rate	7%	per annum in Pakistan
Insurance and taxes	4%	of initial cost
Repair & Maintenance	25%	of initial cost
Daily useful hour	12	including battery storage
Avg. energy generated by SMC/h	2.0 kWh	with DNI ranging between 650 to 800 Wm^{-2} on a sunny day
2.0 kVA generator requires appx.	0.9 Lh^{-1}	of gasoline to generate equivalent energy
	0.7 Lh^{-1}	of diesel to generate equivalent energy
	2.0 kWh	units of electricity
Savings per hour	0.63 USD	using gasoline @ 0.70 USD/L
	0.51 USD	using gasoline @ 0.73 USD/L
	0.25 USD	using gasoline @ 0.13 USD/kWh
For SMP		
Total initial cost	2,201 USD	1 USD = 159 PKR
Expected Life of CSR	10 year	~ 22,000h @ 6 useful hd^{-1}
Salvage value	10%	of initial cost
Interest rate	7%	per annum in Pakistan

Insurance and taxes	4%	of initial cost
Repair & Maintenance	25%	of initial cost
Daily useful hour	6	on a sunny day
Avg. energy generated by SMC/h (Solar thermal + PV)	3.5 kWh	with DNI ranging between 650 to 800 Wm^{-2} on a sunny day
3.5 kVA generator requires appx.	1.6 Lh^{-1}	of gasoline to generate equivalent energy
	0.9 Lh^{-1}	of diesel to generate equivalent energy
	3.5 kWh	units of electricity
Savings per hour	1.13 USD	using gasoline @ 0.70 USD/L
	0.66 USD	using gasoline @ 0.73 USD/L
	0.44 USD	using gasoline @ 0.13 USD/kWh

The individual and total cost estimation per hour of all economic factors and the calculations showed that 0.256 and 0.209 USD per hour were required to operate the SMC and SMP respectively after the initial investment. Based on the available economic data, the break-even point analysis was performed to determine the payback period of SMC and SMP in comparison with other conventional resources. The useful working hours are plotted against the expenses to calculate the break-even point for each case and represented in Fig. 5.5 and 5.6.

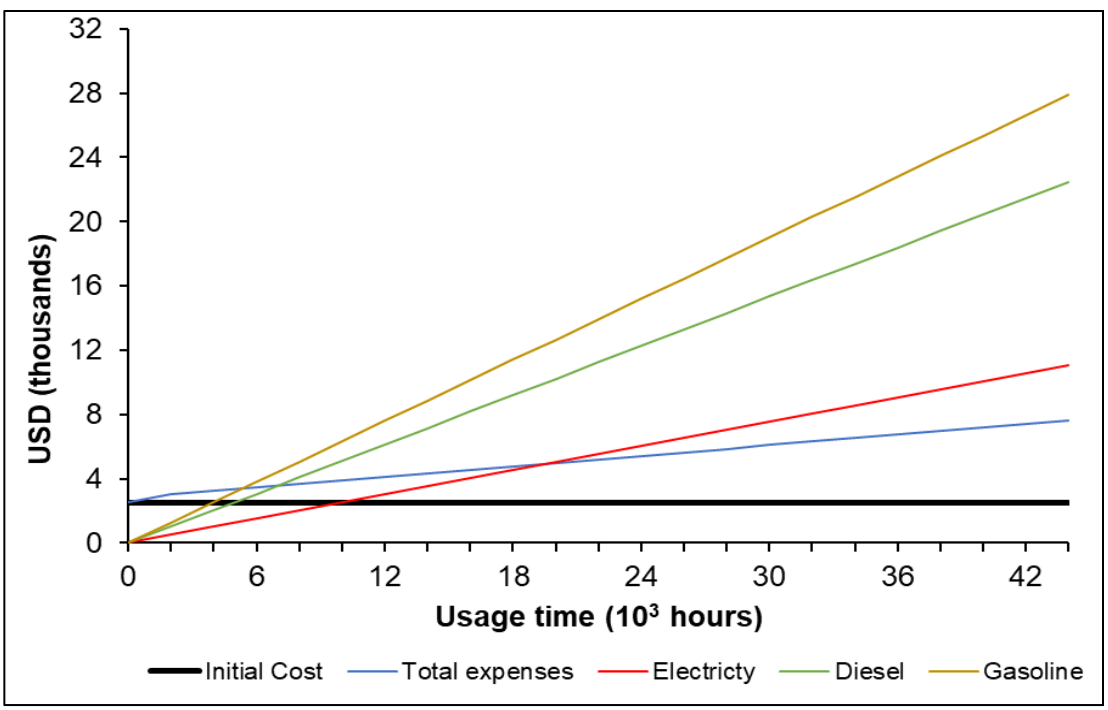

Figure 5.5: Break-even analysis for SMC

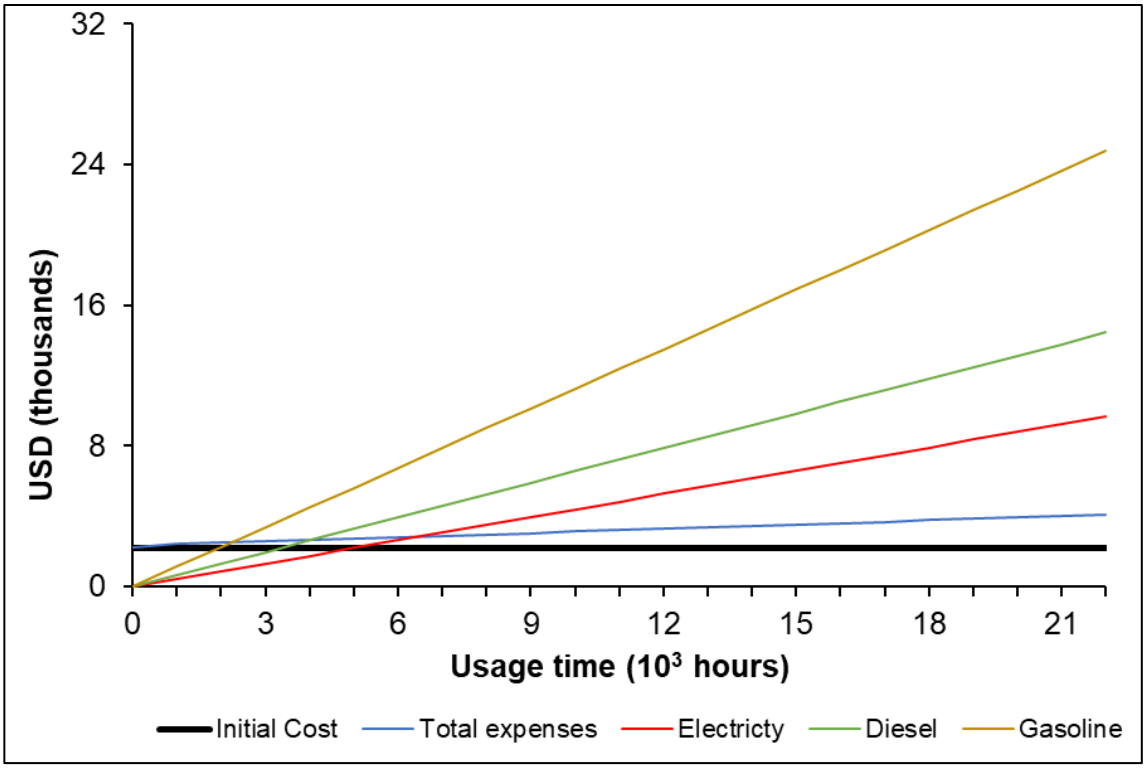

Figure 5.6: Break-even analysis for SMP

The break-even analysis shown in Fig. 5.5 shows the payback period of SMC which was estimated to be 5,700 (~1.3 year), 7,800 (~1.8 year) and 19,800 (~4.5 year) useful working hours if gasoline, diesel and electricity were used for equivalent energy generation respectively. After the payback period, the total revenue generated in expected life span of SMC was estimated to be 20,257, 14,872 and 3,457 USD corresponding to gasoline, diesel and electricity used as source respectively. Similarly, in break-even analysis (Fig. 5.6) for SMP, the payback period was estimated to be 2,400 (~1.1 year), 4,200 (~1.9 year) and 5,900 (~2.7 year) useful working hours if gasoline, diesel and electricity were used for equivalent energy generation respectively. The total revenue generated in expected life span of SMC was estimated to be 20,673, 10,354 and 5,586 USD corresponding to gasoline, diesel and electricity used as source respectively.

The processing cost per liter of milk, both for chilling and pasteurization, was calculated to be 0.003 USD with these solar powered technologies which are far lower that than the estimated processing costs of milk processors i.e., 0.2 USD per liter (FAO, 2011).

5.5 Carbon Emission Analysis

In the perspectives of global warming and climate change, these milk processing systems were also evaluated for CO_2 emission savings over their expected life span of 22,000 h (~10 years). The Solar Milk chiller and Solar Milk Pasteurizer are capable to produce about 2.0 and 3.5 kW solar based energy per hour in all the seasons for on-farm milk processing, respectively (Ref.). Based on these results, it has been estimated that nearly 1012- and 886-MWh useful process energy can be produced by SMC and SMP, respectively in their entire operational life. The results of carbon emission against this amount of energy generation with different non-renewable energy resources are graphically demonstrated in Fig. 5.7 and 5.8.

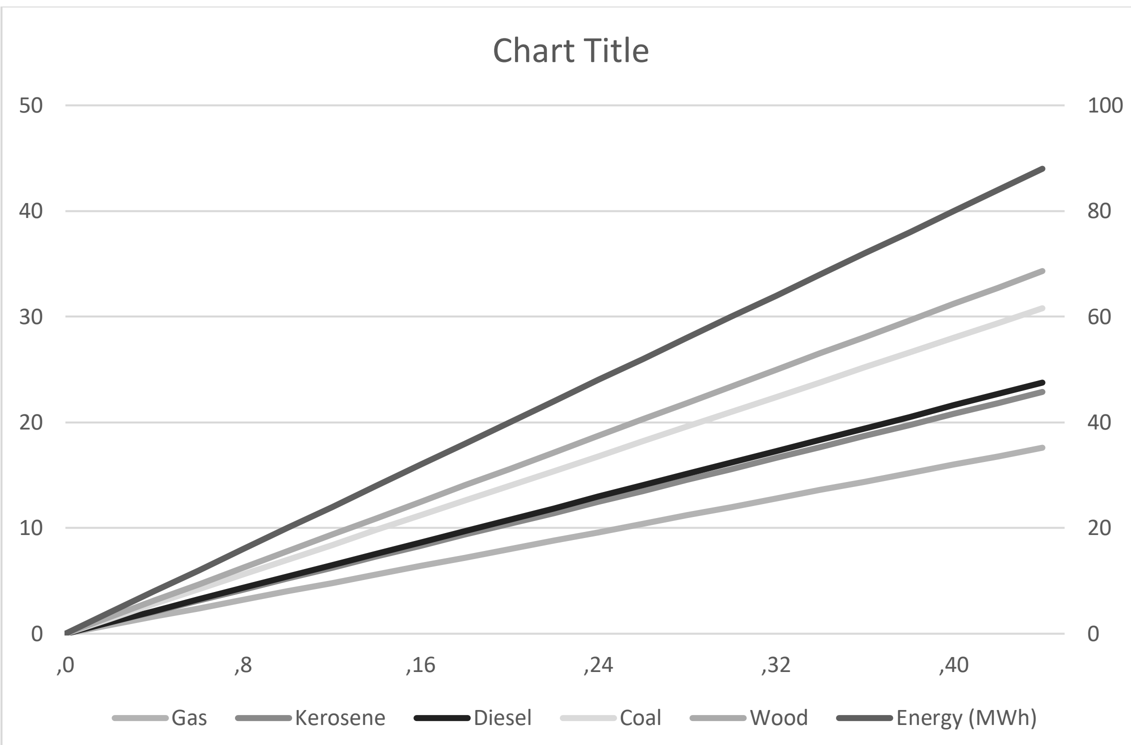

Figure 5.7: CO2 emission savings by Solar Milk Chiller during milk chilling

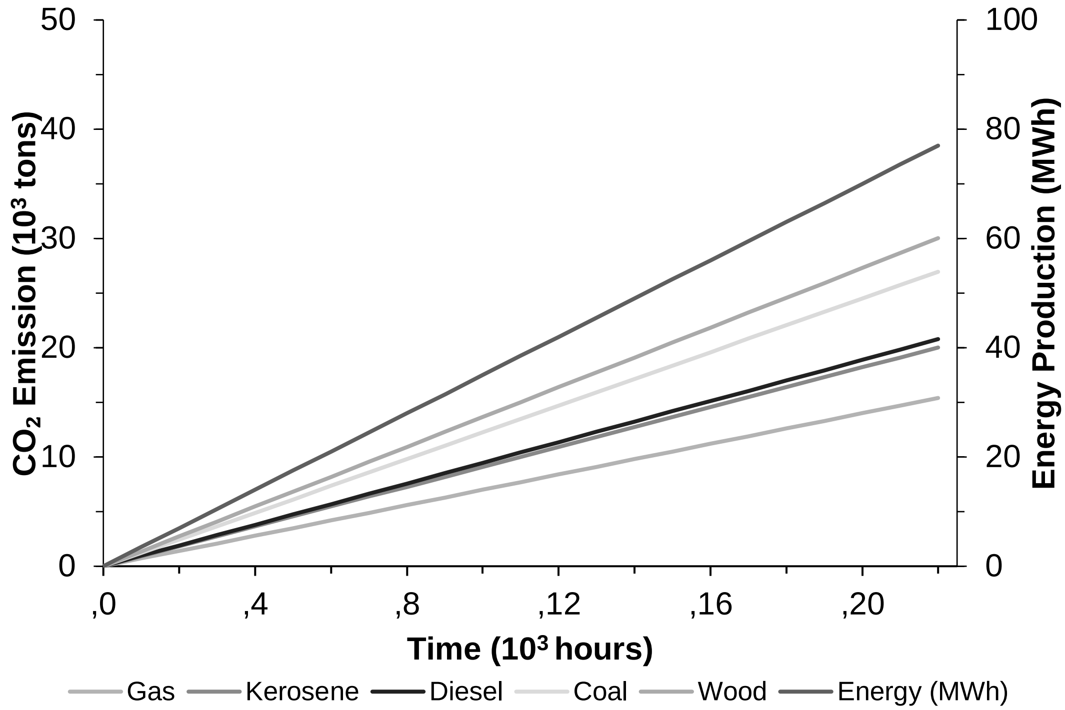

Figure 5.8: CO2 emission savings by Solar Milk Pasteurizer during milk pasteurization

It is evident from the Fig. 5.8 that for equivalent energy production for milk chilling (1012 MWh), wood being used as fuel source will emit 395 thousand tons of CO_2 followed by coal (354 thousand tons), diesel (273 thousand tons), kerosene (263 thousand tons) and natural gas (202 thousand tons). Similarly, wood, coal, diesel, kerosene and natural gas will contribute about 345, 310, 239, 230 and 177 thousand tons of CO_2 respectively to the atmosphere for generating same amount of energy for milk pasteurization (886 MWh) with SMP (Fig. 5.8). These analyses revealed that SMC and SMP are promising green technologies for milk processing which can also effectively address the global warming issue particularly in terms of carbon emission savings.

5.6. Conclusions

Milk is nature gifted wholesome diet for human of all ages and all genders but, the results of the current study is astonishing and entirely different from this statement. The findings of the study revealed that a white watery liquid is provided to the consumers particularly by the vendor open milk shops including urban and peri-urban areas, and milkmen supplying milk at homes. A large percentage of tested samples found with bad odor, unusual color, thin texture, very depreciated nutritional value, and extensive adulteration specially by water. It can be envisaged that probably everyone involved in the milk value chain contaminated the milk to some extent directly or indirectly but very intentionally.

Concurrently, the company packed processed milk samples, although found with negligible adulteration, but their nutritive values were trended towards the bottom line of the standard ranges because nearly all the milk processing companies partially skimmed the milk for by products and then supply it to the consumers for drinking along with high sale prices.

In comparison, the milk processed with SMC and SMP has been found better in all quality and consumer acceptability aspects than the local market milk and company processed milk. There were zero adulteration, and 100% hygiene conditions were observed in the solar processed milk as the pure and fresh milk was directly precured from the UAF Dairy Farm.

The break-even point analysis in terms of energy showed that SMC and SMP has the capacity to pay back capital cost in 1.3 to 4.5 and 1.1 to 2.7 years respectively depending upon the type of non-renewable source used for equivalent energy generation. The processing cost per liter of milk, both for chilling and pasteurization, was calculated to be 0.003 USD. Being eco-friendly technologies, the developed solar based technologies will combinedly generate about 1892 MWh energy with zero carbon emission.

In a nutshell, the developed Solar Milk Chiller (SMC) and Solar Milk Pasteurizer (SMP) offer viable solution to meet the challenges faced by the local milk value chain. These innovative and decentralized solar based milk processing technologies provide the opportunity for on-farm quality processing of milk under controlled operating conditions which can contribute towards resolving the existing technological constraints for the milk producers and quality constraints for the consumers.

Acknowledgment

The authors gratefully acknowledge the International Center for decent work and development (ICDD) University of Kassel Germany for funding of this project. We would also like to appreciate Deutscher Akademischer Austauschdienst (DAAD) and Fachgebiet Agrartechnik Uni Kassel Witzenhausen (AGT) for their cooperation and support during pre and post research activities for the present study. Finally, we would like to acknowledge Department of Energy Systems Engineering, University of Agriculture Faisalabad Pakistan (ESE-UAF) for providing technical assistance and site place for the development and installation of systems used for the project.

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6. General discussion and conclusion

The rich quality dairy products provide a great source of essential nutrients in terms of healthy and nourishing food which is demanding worldwide gradually due to overpopulation particularly in developing countries. Being a natural liquid food, milk is a complete nutritional diet containing all the essential minerals such as protein, fat and vitamins. However, improper post milking handling and storage resulting in wastage due to microorganisms and bacterial multiplication. The present study enabled the application of decentralized solar-based milk pasteurization and chilling unit for the rural communities in Pakistan. To achieve pasteurization, innovative and efficient medium temperature solar technologies like SC and ETC were employed. For chilling process, one tonne of refrigeration unit powered by PV panels (2kWp) using VRF technology was used. Finally, the microbial quality analysis of processed milk was carried out in comparison to locally available fresh and packaged milk.

According to FAO, undernourished people in the world is more than 1 billion; most of the people are from developing countries. According to international phase classification (IPC), 29 districts in Pakistan are classified under Phase 3 “Crisis” and 04 districts as phase 4: “Humanitarian Emergency; these miserable conditions are attributed to lack of decentralized processing facilities (Aworh, 2008). Therefore, this is the dire need to take steps on priority basis to handle this critical situation in Pakistan as well as in other third world countries. The weather is tropical where temperature reaches above 50ºC in most of the regions, especially during summer. It is worth mentioning here that most of these countries lie in tropical regions where high temperature and peak solar irradiation (5-7 $kWhm^{-2}d^{-1}$) are available that can be utilized effectively to address medium temperature solar-based on-farm processing.

Energy required to pasteurize 100L of milk were calculated to be 4.68 and 4.22 kWh respectively for a temperature difference of 35-40°C. Under practical conditions, heat energy consumed for the milk pasteurization system coupled with SC and ETC was recorded to be 3.56 kWh and 3.91 kWh respectively; this value increases from 3.78 – 4.32 kWh to pasteurize the same milk batch size for a temperature difference of 35-40°C. Experiments were conducted using different batch sizes (50L, 100L, 150L and 200L) to cool down the raw milk from 30ºC to 4ºC. During the optimization phase, the comparative power required to run various types of compressors (reciprocating, rotary with capacitor and rotary with VRF) were found to be 1.8 kW, 1.2 kW and 0.8 kW respectively whereas the torque loads were noted to be 3.3 kW, 1.6 kW and zero kW. The developed solar based technologies showed promising quality of milk processing in physical, chemical, hygienic, adulteration and consumer acceptability aspects over the compared milk sources. Fat (5.4%), solid-not-fat (9.1%), salts (0.7%), protein (3.9%), lactose (4.2%), total solids (14.5%), pH (6.85), density (1.031 kg/l) and freezing point (-0.532°C) of solar processed milk were found within the standardized ranges required for good quality milk. The processing cost per liter of milk, both for chilling and pasteurization, was calculated to be 0.003 USD using these solar powered technologies. The overall flow chart of whole present study has been shown in Fig. 6.1.

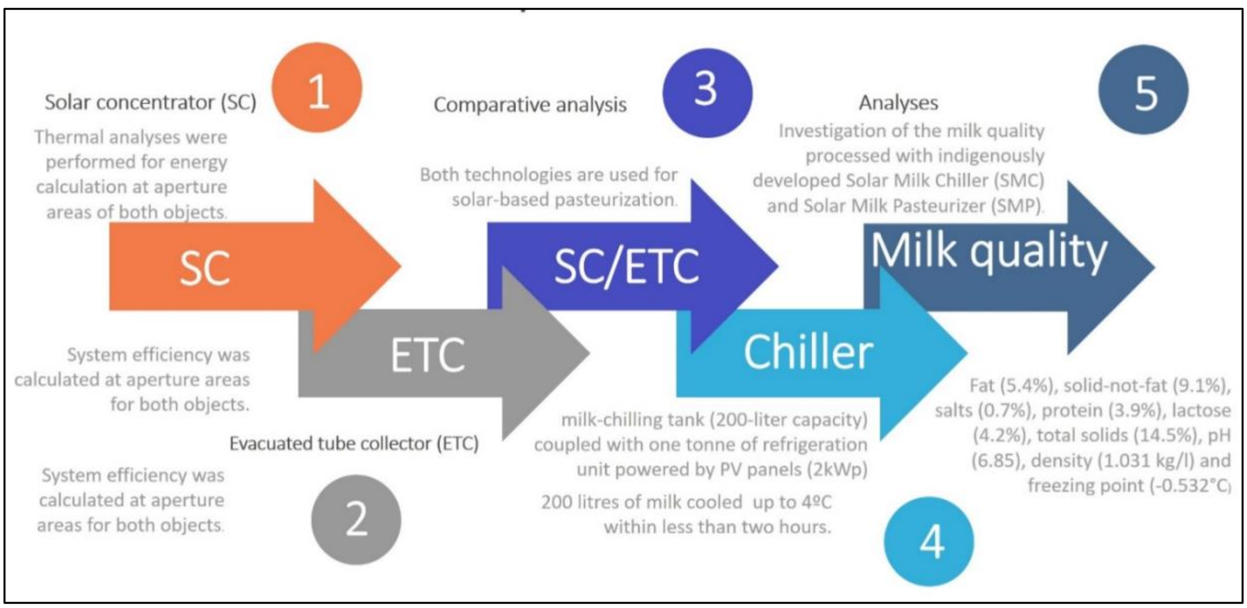

Figure 6.1: Overall flow chart of the present study

The baseline surveys conducted in the present study and proved helpful in determining the exact situation of the existing milk supply chain including major post milking problems of the farmers. The farming community can get benefit from the developed technologies and can save their milk from spoilage specially during high temperature days. The processing facility can provide a valuable solution to increase the shelf life of the milk. Once the milk is pasteurized and chilled at 4°C, it is safe for use. The use of hydrogen peroxide can increase the shelf life of the milk. The fresh process milk can be easily transported to selling points located in vicinity of the urban places. This can result in creating new jobs and income generation opportunities for the farming communities in Pakistan.

6.1 Development of solar-based milk pasteurizer with Solar Concentrator and Evacuated Tube Collector

Solar based milk pasteurizer enables decentralized preservation of milk quality at zero or minimum operating cost, particularly in remote areas of Pakistan. With the introduction of innovative and efficient medium temperature solar technologies, two approaches can be conveniently used to accomplish pasteurization i.e., SC and ETC. The present study focused on a widespread comparative thermal analysis of above-mentioned techniques for a solar-driven milk pasteurization unit. The detailed thermal analyses of both the solar based systems were conducted to investigate the useful energy and losses during the process of milk pasteurization. The available energy values were found to be 8.11 and 5.63 kWh at the aperture areas of SC and ETC, respectively. Energy required to pasteurize 100L of milk were calculated to be 4.68 and 4.22 kWh respectively for a temperature difference of 35-40°C. Some of the recent studies regarding ETC, Shafieian et al. (2019) proposed that the temperature of the solar working fluid increased as the number of glass tubes increased, however, the temperature increase rate decreased and became comparatively insignificant for the number of tubes greater than 25 to 30. They attributed this reduced or even stable temperature increase to increased surface area and consequently increasing absorption capacity of ETC. Our findings are completely inconsistent with the above-mentioned findings as we observed that the temperature of working fluid (water in our case) increases with increase in number of tubes. The temperature was restricted to 40ºC in case of 15 tubes, however, a significant rise was noted as the number of tubes increased to 45. For Faisalabad region during bright sunny summer days, the above-mentioned fact is true which slightly fluctuates in case of a cloudy/dense day. We also noted that for this region, rate of increasing temperature stabilizes at 45 tubes as opposed to the Perth (Australia) where Shafieian et al. (2019) made the experimental setup with 25 tubes. In our case we have employed a storage tank (fully insulated with PU) and extra energy is stored in the storage tank which can be used for next batches.

Another important factor involves the regional wind velocity of the study area. The average wind velocity for the Faisalabad region is 2m/s. We observed a negligible effect on temperature variation in ETC. Similarly, Du et al. (2013) prepared a platform for studying the performance of a HPSC in a solar water heating system. The obtained results including collector outlet temperature, instantaneous efficiency, and pressure drop were presented in detail. The maximum achieved efficiency of the collector was 60% which occurred at the solar radiation of 860 W/m^2. Whereas, in our research the efficiencies for SC and ETC were recorded to be 58% and 74% respectively under the average solar radiation of 750 W/m^2. These figures conclude that the efficiency of improved milk pasteurization employing ETC, and Sc are greater than the research conducted by Du et al. (2013).

The results showed that the contact thermal resistance decreased to a great extent. Rassamakin et al. (2013) proposed the application of specially extruded aluminum heat pipes in the HPSC of a solar water heating system to reduce the contact thermal resistance. Under practical conditions, heat energy consumed for the milk pasteurization system coupled with SC and ETC was recorded to be 3.56 kWh and 3.91 kWh respectively; this value lies from 3.78 – 4.32 kWh to pasteurize 100L of milk for a temperature difference of 35-40°C. The predicted value of efficiency for SC and ETC were found to be 57.71 and 74.88% respectively. The efficiency values under field conditions for SC and ETC were found to be 54 and 71.41% respectively. In both cases (theoretical and practical), efficiency of ETC is significantly higher than that of SC. Since the optical losses and thermal losses in ETC are very less as compared to that of SC. The heat energy losses per unit time (W) were also calculated in terms of optical losses study concluded that both the systems can be effectively utilized for the milk pasteurization; however, ETC based solar milk pasteurization system proved to be more efficient, simpler in design, cheaper, stable, compact, portable, and cost effective and provides excellent opportunity for decentralized milk processing.

In the analysis of the thermal performance of the evacuated tube solar collector, the influence of real variable weather (i.e., solar irradiance, ambient temperature, wind speed) and operating conditions (working fluid temperature at the inlet and outlet of the collector) were considered. The average value of the solar irradiation for the considered time period (2 months) was recorded to be 3.1 kWh/(m^2·d) while the mean value of the ambient temperature was recorded to be 292.6 K. The average values of the useful heat gain from the solar collector in July and August reached 163 W/m^2 and 145 W/m^2, respectively. The average monthly thermal yield for the solar collector was 478.8 MJ/month. The average monthly energy efficiency of the heat pipe evacuated tube solar collector in July and August were 45.3% and 32.9%, respectively. The average monthly exergy efficiency of the solar collector amounted to 2.62% in July and 2.15% in August. It was found that an increase in the temperature difference between the mixture of water and propylene glycol at the solar collector inlet and ambient temperature causes a slight increase in the exergy efficiency and a decrease in the thermal efficiency. These findings are consistent with the results of the experimental investigations carried out by Jafarkazemi et al. (2016) and Olcha et al. (2021). The increase in the wind velocity contributes to the decrease in both energy and exergy efficiency of the evacuated tube solar collector.

The available energy was estimated to be 8.10 and 5.63 kWh at the aperture areas of SC and ETC, respectively. Under the constant range of solar radiations (GHI), the pasteurization process is quite smooth with gradual increase in temperature and process completed in 80-90 minutes to reach a temperature of 63°C from ambient temperature. The total power consumed was recorded to be 2.67 kW to reach this pasteurization temperature. The total energy required for the pasteurization of 100L batch of milk is 3.57 kWh. Though results showed that solar milk pasteurization can be successfully done using SC yet under the average beam radiation range of 686 Wm^{-2}, the overall efficiency of the system was found to be only 58%. On the other side, in case of ETC, the overall efficiency of the system was found to be 74%. These results are in accordance with results obtained from predicted values (54% for SC and 71% for ETC) showing the reliability of the developed algorithm. Research concludes that both systems can be effectively used for the milk pasteurization system, however, the system coupled with ETC is more efficient, simpler in design and provides thermal storage to continue the process under varying weather conditions.

6.2 Development of solar-based milk chiller with Variable Refrigerant Flow

Fresh milk spoils due to increased temperature in villages or remote areas. Therefore, chilling milk was the solution to maintain its quality. The existing chillers were mostly with old and highly energy consuming technology. Very few farming and the middleman community had those chillers but not using anymore due to their high energy operating costs due to the presence of conventional reciprocating compressors as well as low specific heat refrigerants which were not even environment friendly. During the baseline surveys, this was found that the high energy consumption in chilling process was also a major constraint that limited the use of chillers and hence resulted the milk spoilage due to non-availability of cooling facility. Thus, the idea to promote the chilling phenomena was designed keeping in mind this fact that the technology must be environment friendly as well as energy efficient. Therefore, firstly, the chiller was designed with conventional reciprocating compressor using R-22 refrigerant. However, the observed results were same as found by previously designed chillers. Secondly, the solar system was coupled with a hybrid inverter, and it was found that during the torque load kick, some of the power was drained from the grid electricity because the solar PV system was unable to bear the torque load of that type of system. Hence this type of system was not favorable for a decentralized solution to the famers where limited or no access to the grid electricity was possible. During the second phase of experiments, the compressor was replaced with a rotary type and refrigerant was changed with environmentally friendly R-410 having better physical and thermal parameters to extract heat from a cold body (milk chamber) and throw it away to a hot body (ambient air). The results found using this technology were quite encouraging as compared with the old conventional reciprocating technology but still torque load was too high to be taken from PV array successfully. Actually, a 2 kW_p solar PV system was designed that can run 1 kW compressor motor under normal operation but the load was exceeding 75% of its capacity during the torque load i.e. the starting of compressor. During the third phase of chiller compressor optimization, a VRF technology was used to integrate the compressor motor which can run the system efficiently and smoothly without any torque load. This VRF technology maintains the refrigerant flow following the required cooling loads intermittently without tripping the compressor; thus, eliminating the uneven power impulses and surges during milk processing. In this system with a single, large-capacity scroll compressor, the same compressor starts and runs when there is demand and no redundancy is available if the compressor fails. It is pertinent to mention here that a VFD would be better than a soft starter because the speed of the compressor is needed to be varied with varying milk cooling process.

In this study the size of the chiller and pasteurizer were 200L and 100L respectively. This was done based on the baseline surveys where it was concluded that a group of farmers can process their milk together. The energy calculations were also made with the same amount of capacity i.e., 200L of milk must be rapidly chilled from 63 to 4ºC within a time interval of 120 minutes as per WHO standards. It was calculated that one ton of refrigeration was required to cool down the milk at this storage temperature (4°C). The solar PV power required to run a one tone of refrigeration (TR) cooling load was calculated to be 2kW$_p$; a 300Ah battery backup was used to provide constant power throughout the day employing a 3-kW hybrid inverter.

Similarly, in case of pasteurization, quick solar thermal power was required, and this power was taken from high temperature solar thermal collectors (SC and ETC) to pasteurize 100L of milk. Energy calculations were made before designing the system using physical and thermal characteristics (density, specific weight, specific heat etc.) of milk. SC of 10 m^2 surface area was used and the desired temperature was obtained within the permissible time limit as per WHO standards. Both SC and ETC based milk pasteurization technologies provided good results, but the ETC was found to be more efficient and convenient to use in terms of size, handling and compactness.

In case of chiller, first, a reciprocating type compressor with R22 refrigerant was used and torque load was recorded to be 3.8-4kW and the average running load was

2.4kW. Unfortunately, the running load exceeded our designed solar system capacity (calculation made with respect to cooling of 200L of milk in 120 minutes, the WHO standards). A hybrid inverter was used to run the chiller system at rated power taking solar power on priority and utility/battery power as a second priority. To reduce the torque load and to reduce the resistance of reciprocating compressor, the existing compressor was replaced by a rotary type of compressor along with capacitor and R410 refrigerant was used to reduce the torque load and running load and these values were found be 1.3kW and 1.1kW respectively. So, by replacing compressor type and refrigerant the torque load and running load significantly reduced, however, our desired objective was still not fulfilled. Finally, VRF technology was used which minimized the torque load to zero and running load was less than 1kW which made this chiller an energy efficient, compatible with the designed PV array and best suited for decentralized chilling application even at off-grid locations.

The VRF technology not only solved the toque load issue successfully but also reduced the size of peak power requirement of PV array. The experimental and modeled predicted power consumption and chilling time under different batch sizes revealed good correlation co-efficient. It was found that about one-tonne of refrigeration (TR) unit was sufficient to reduce the temperature of 200L of milk from 63 to 4ºC within two hours which is recommended time as per WHO standards for on farm milk processing.

6.3 Milk quality analysis

Milk is nature gifted wholesome diet for human of all ages and all genders. The findings of the study revealed that a white watery liquid is provided to the consumers particularly by the vendor open milk shops including urban and peri-urban areas, and milkmen supplying milk at homes. A large percentage of tested samples found with bad odor, unusual color, thin texture, very depreciated nutritional value, and extensive adulteration specially by water. It can be envisaged that probably everyone involved in the milk value chain contaminates the milk to some extent directly or indirectly, but it varies intentionally. Concurrently, the company packed processed milk samples, although found with negligible adulteration, but their nutritive values were trended towards the bottom line of the standard ranges because nearly all the milk processing companies partially skimmed the milk for byproducts and then supply it to the consumers for drinking along with high sale prices. Local market milk samples only were analysed for the adulteration in comparison with solar processed milk. The findings of determination of adulterants in local market milk and solar processed milk samples were astonished. It is clear from the results that local market milk samples (urban vendor milk, peri-urban vendor milk and milkmen milk) were extensively adulterated with water (93, 89 and 71%), urea (66, 59 and 37%), formalin (31, 21 and 9%), and cane sugar (76, 81 and 57%) respectively. Only a minute fraction of starch (2%), H_2O_2 (2%) and detergents (1%) adulteration were found in urban sold milk samples. The solar processed milk was found adulteration-free in all aspects.

In comparison, the milk processed using solar energy (SMC and SMP) has been found better in all quality and consumer acceptability aspects than the local market milk and company processed milk. There were zero adulteration, and 100% hygiene conditions were observed in the solar processed milk as the pure and fresh milk was directly procured from the UAF Dairy Farm. The break-even point analysis in terms of energy showed that SMC and SMP had the capacity to pay back capital cost in 1.3 to 4.5 and 1.1 to 2.7 years respectively depending upon the type of non-renewable technology used. The processing cost per liter of milk, both for chilling and pasteurization, was calculated to be 0.003 USD.

6.4 Strengths, weaknesses, opportunities, threats (SWOT) analysis of the study

All machines (units) were developed successfully with efficient performance theoretically and practically with satisfactory milk quality. The major issue of improper post milking facilities at the farm-scale level was resolved by fabrication, however, the designed units cannot be provided to the farmers directly without any official support at government, academia or any other organizational level. This clear-case issue needs the involvement of the UAF Food sciences and dairy department with further support of the social science and extension department to organize an awareness campaign for the farmers to implement the use of these machines. Furthermore, Punjab Food Authority must pass a resolution and legislation to discourage unpackaged milk transportation and distribution. Fortunately, they have already imposed a ban on transportation, but the problem exists in the grassroots level which requires further steps.

6.4.1 Strengths

- Development of an improved solar based chiller for decentralized application.
- Development of solar based milk pasteurization using ETC and SC.
- Estimation of thermal and optical losses calculation paved the way to future studies.
- Milk pasteurization and chilling as per WHO standards.
- No risk of power failure due to independency of grid electricity connection.

6.4.2 Weaknesses

- Lack of technical know how to run the integrated system by uneducated farmers.
- Lack of repair and spare facilities at remote places.

6.4.3 Opportunities

- Excellent opportunity to process the fresh farm milk at the farmer’s site.
- Rural development by providing on farm processing of milk. The opportunities can be achieved in terms of short-medium terms goals as shown in Fig. 6.2. These goals are beyond the scope of the present study due to time, resources and infrastructure limitations.
- Step forward to uplift small-scale farmer
- Elimination rule of middleman.

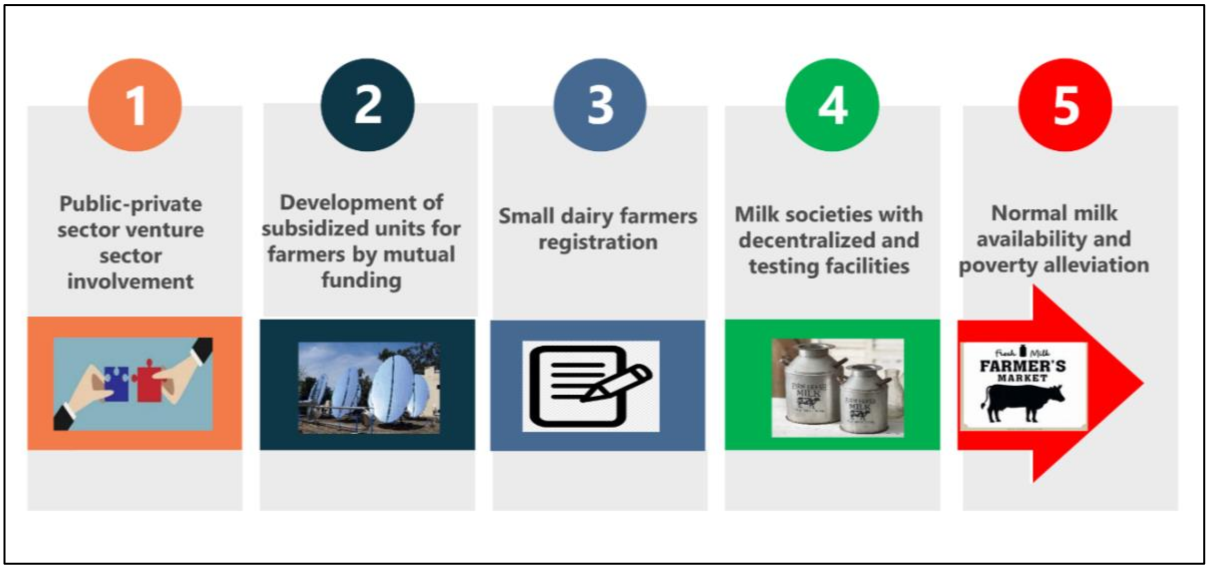

Figure 6.2: Opportunities in terms of short-medium term goals

6.4.4 Threats

- Initial cost is too high to be afforded by farming community.
- Improper CIP may result economic loss in terms of complete batch spoilage.

The designed units have more strengths and opportunities as compared to the weaknesses and threats which make it a successful solution for farmer communities.

6.5 Critical review and outlook

The research objectives that led to the preparation of this study (see page 7) can be answered as follows:

- Baseline surveys successfully concluded the situation of the milk distribution system and quality of milk supplied. Also covered the problems and challenges of the farming community and available storage and processing facilities. Hence, the results led to the fabrication of the technologies.
- Developments of solar milk pasteurizers integrated with solar concentrator and evacuated tube collector were successfully done and the machines were optimized to process milk with solar energy
- Efficient Solar milk chiller was developed using VRF and was tested at farm level successfully and operated at minimum torque load.

- Comprehensive quality and economic analysis of processed milk led to successful accomplishment of the study as the results of the processed milk were found satisfactory in terms of quality of milk.

6.6 Conclusion

In a nutshell, the present study addressed the raised research question in successful manner by accomplishing all research objectives by developing decentralized SMP, SMC, comprehensive milk quality and economic analysis for dairy farming communities. These units provide a viable solution to meet the challenges faced by the local milk value chain. These innovative and decentralized solar based milk processing technologies provide the opportunity for on-farm quality processing of milk under controlled operating conditions which can contribute towards resolving the existing technological constraints for the milk producers and quality constraints for the consumers. The opportunities can be achieved gradually after getting farmer registration and sufficient funding from the mutual collaboration of public and private sector of dairy farming as suggested earlier. The study concludes that with the introduction of innovative solar and refrigeration technologies, decentralized/on-farming milk processing is possible which will not only process the fresh available abundant supply of milk at farm level but will also provide an extraordinary opportunity of value addition and income generation for farming community in rural areas of developing regions. The results showed that solar milk pasteurization can be successfully done using SC and ETC under the average solar radiation range in Faisalabad. It was also concluded that both systems can be effectively used for the milk pasteurization system, however, the system coupled with ETC is more efficient, simple in design and provides thermal storage to continue the process under varying weather conditions.

A large percentage of tested samples found with bad odor, unusual color, thin texture, very depreciated nutritional value, and extensive adulteration specially by water. It can be envisaged that probably everyone involved in the milk value chain contaminated the milk to some extent implicitly or explicitly. Although, the packaged milk samples found negligible adulteration, however the proclivity of nutritional value was still lower preserved as per food quality standards. It was mainly attributed to the addition of skimmed milk and other food additives which enhance the taste and thickness. The designed units provide a viable solution to meet the challenges faced by the farmers, consumers and other entities of local milk value chain.

6.7 Future recommendations

The capacity and maintenance of the developed SMP and SMC units can be enhanced in future using the following techniques

- The current study designed for 100L and 200L milk batch sizes for pasteurization and chilling units, respectively. The milk batch size and solar capacity can be increased depending upon the available milk requirement and resources.
- The chilling unit can be mounted on a vehicle to use it as a mobile unit.
- For the large-scale milk chilling vapour absorption system can be used.
- The auxiliary heater of the pasteurization system under the storage tank may be operated with solar PV system while during pasteurization process the solar PV is standby and not in use.
- To ensure cleaning of the developed units a built in CIP setup can be introduced in future.
- According to the available resources an automatic milk packaging machine can be couples with these units to increase milk shelf life.

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7. Summary

Solar-based milk pasteurization enables decentralized maintenance of milk quality, particularly in remote areas of developing countries. With the introduction of innovative and efficient medium temperature solar technologies, two approaches can be conveniently used to accomplish pasteurization using solar concentrator (SC) and evacuated tube collectors (ETC). The present study focusses on a widespread comparative thermal analysis of above-mentioned techniques for a solar-driven milk pasteurization unit installed at Solar Park, University of Agriculture Faisalabad, Pakistan (31.4456° N, 73.1356° E). For this purpose, a 100L stainless steel (SS-304; food grade) cylindrical milk pasteurizer was fabricated with the dimensions of 558.8 mm diameter and 432 mm length, in combination with a standing Scheffler fixed focus paraboloidal concentrator (10 m^2), steam receiver and a milk pasteurizer. Second set of milk pasteurization system comprises an ETC, hot water storage tank and a milk pasteurizer unit along with all mountings and accessories. The detailed thermal analyses of both the solar based systems were conducted to investigate the useful energy and losses during the process of milk pasteurization. The available energy was estimated to be 8.11 and 5.63 kWh at the aperture areas of SC and ETC, respectively.

Energy to pasteurize 100L of milk were calculated to be 4.68 and 4.22 kWh respectively for a temperature difference of 35-40°C. Under practical conditions, heat energy consumed for the milk pasteurization system coupled with SC and ETC was recorded to be 3.56 kWh and 3.91 kWh respectively; this value lies from 3.78 – 4.32 kWh to pasteurize 100L of milk for a temperature difference of 35-40°C. The predicted value of efficiency for SC and ETC were found to be 57.71 and 74.88% respectively. The efficiency values under field conditions for SC and ETC were found to be 54 and 71.41% respectively. In both cases (Theoretical and practical), efficiency of ETC is significantly higher than that of SC. This is due to the fact that the optical losses and thermal losses in ETC are very less as compared to that of SC. The heat energy losses per unit time (W) were also calculated in terms of optical losses study concluded that both the systems can be effectively utilized for the milk pasteurization; however, ETC based solar milk pasteurization system proved to be more efficient, simpler in design, cheaper, stable,

compact, and cost effective and provides excellent opportunity for decentralized milk processing.

Being a natural liquid food, milk is a complete nutritional diet containing all of the essential minerals such as protein, fat and vitamins. However, improper post milking handling and storage resulting in wastage due to microorganisms and bacterial multiplication. Fresh milk was spoiled due to increased temperature in developing countries. While using solar PV, minimizing torque load of the cooling machines was big challenge for the smooth functioning of the milk chilling system especially for the conventional (reciprocating) type of compressors; variable refrigerant flow (VRF) technology not only solved toque load problem but also reduced the size of peak power requirement of PV array. This system comprises a milk-chilling tank (200L capacity) coupled with one tonne of refrigeration unit powered by PV panels (2kWp) and employing VRF technology to make system more energy efficient by minimizing the torque load. Experiments were conducted using different batch sizes (50L, 100L, 150L and 200L) to cool down the raw milk from 30ºC to 4ºC. During the optimization phase, the comparative power required to run various types of compressors (reciprocating, rotary with capacitor and rotary with VRF) were found to be 1.8 kW, 1.2 kW and 0.8 kW respectively whereas the torque loads were noted to be 3.3 kW, 1.6 kW and zero kW. The experimental and modeled predicted power consumption and chilling time under different batch sizes revealed good correlation coefficients (R2 = 0.99, $P < 0.0001$). It was found that about one-tonne of refrigeration unit is sufficient to chill 200L of milk up to 4ºC within less than two hours as per WHO standards for on farm processing of milk.

Milk adulteration is very common during processing and in whole supply chain, particularly in least developed countries (LDCs) like Pakistan. The dairy farmers have to sell raw milk due to inadequate farm-gate milk processing facilities leading to economic and quality compromises for producers and consumers respectfully. The current study has been taken up to investigate the milk quality processed with indigenously developed Solar Milk Chiller (SMC) and Solar Milk Pasteurizer (SMP) coupled with an evacuated solar tube collector in comparison with existing milk value chain and techno-economic feasibility of these developed technologies. The quality attributes like fat (5.4%), solid-

not-fat (9.1%), salts (0.7%), protein (3.9%), lactose (4.2%), total solids (14.5%), pH (6.85), density (1.031 kg/l) and freezing point (-0.532°C) of processed milk were found within the standardized ranges. The results of sensory evaluation using a 9-point hedonic scale showed overall likeness towards solar processed milk in terms of taste, color, aroma, and freshness. With an estimated operational lifespan of 10 years, the payback periods for SMC and SMP have been found to be 1.3 to 4.5 and 1.1 to 2.7 years respectively, depending upon the alternate source for equivalent energy generation. The processing cost per liter of milk, both for chilling and pasteurization, was calculated to be 0.003 USD with these solar powered technologies.

Zusammenfassung:

Die solare Milchpasteurisierung ermöglicht eine dezentrale Erhaltung der Milchqualität, insbesondere in abgelegenen Gebieten von Entwicklungsländern. Mit der Einführung innovativer und effizienter Mitteltemperatur-Solartechnologien können zwei Ansätze für die Pasteurisierung genutzt werden: Solar Konzentrator (SC) und Vakuumröhrenkollektoren (ETC). Die vorliegende Studie konzentriert sich auf eine umfassende vergleichende thermische Analyse der oben genannten Techniken für eine solarbetriebene Milchpasteurisierungsanlage, die im Solarpark der University of Agriculture Faisalabad, Pakistan (31,4456° N, 73,1356° E), installiert wurde. Zu diesem Zweck wurde ein zylindrischer Milchpasteur mit einem Fassungsvermögen von 100 Litern aus rostfreiem Stahl (SS-304; lebensmittelecht) mit einem Durchmesser von 558,8 mm und einer Länge von 432 mm in Kombination mit einem stehenden Scheffler-Paraboloid Konzentrator mit festem Brennpunkt (10 m2), einem Dampfbehälter und einem Milchpasteur hergestellt. Das zweite Set des Milchpasteurisierungssystems besteht aus einem ETC, einem Heißwasserspeicher und einer Milchpasteurisierungseinheit mit allen Halterungen und Zubehörteilen. Die detaillierten thermischen Analysen der beiden solarbasierten Systeme wurden durchgeführt, um die Nutzenergie und die Verluste während des Milchpasteurisierungsprozesses zu untersuchen. Die verfügbare Energie wurde auf 8,11 bzw. 5,63 kWh an den Öffnungsflächen von SC und ETC geschätzt.

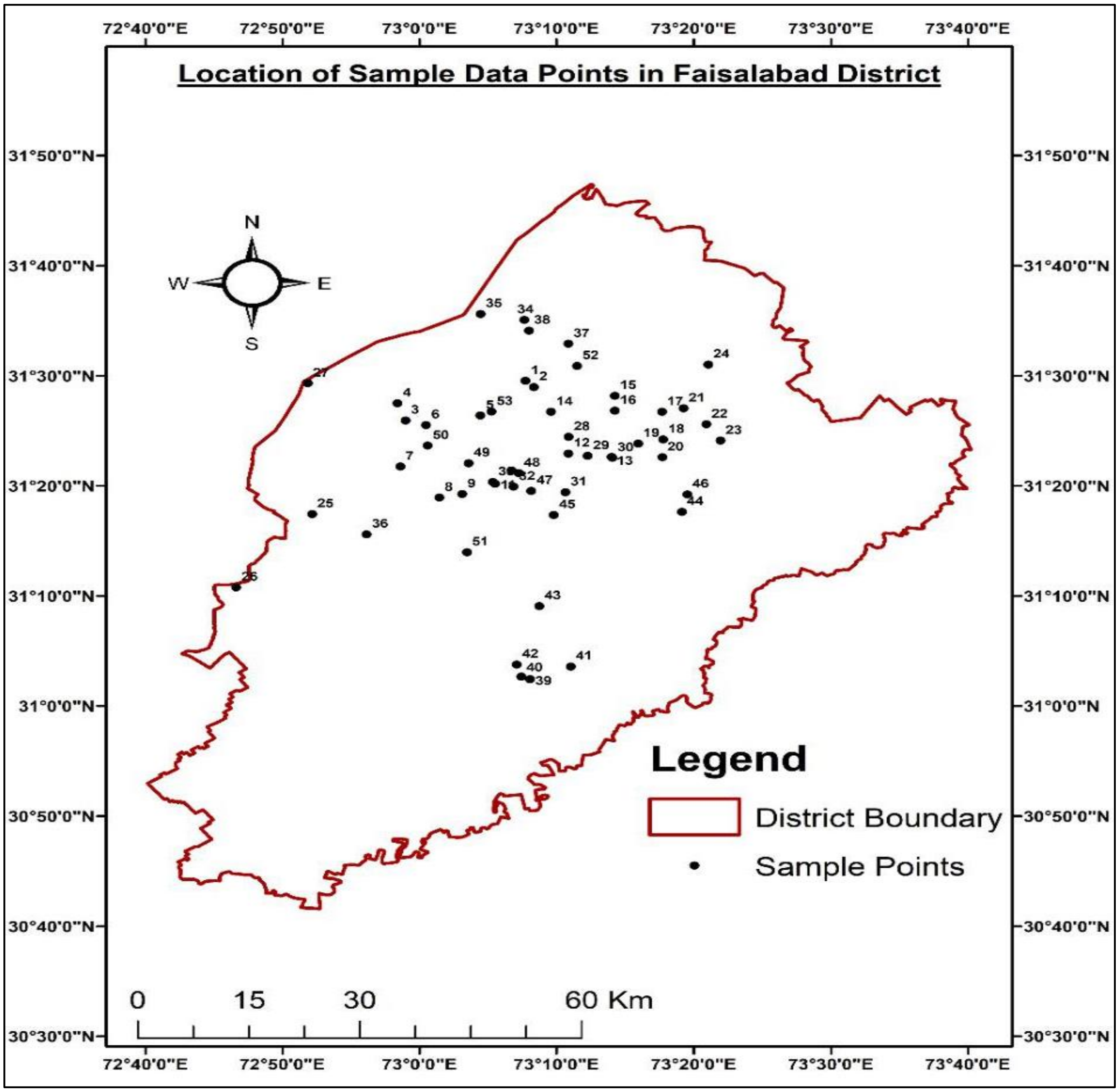
Die Energie für die Pasteurisierung von 100 l Milch wurde auf 4,68 bzw. 4,22 kWh bei einer Temperaturdifferenz von 35-40 °C berechnet. Unter praktischen Bedingungen wurde für das mit SC und ETC gekoppelte Milchpasteurisierungssystem ein Wärmeenergieverbrauch von 3,56 kWh bzw. 3,91 kWh ermittelt; dieser Wert liegt zwischen 3,78 und 4,32 kWh für die Pasteurisierung von 100 l Milch bei einem Temperaturunterschied von 35-40°C. Der vorhergesagte Wert des Wirkungsgrades für SC und ETC wurde mit 57,71 bzw. 74,88% ermittelt. Die Effizienzwerte unter Feldbedingungen für SC und ETC betrugen 54 bzw. 71,41 %. In beiden Fällen (theoretisch und praktisch) ist der Wirkungsgrad von ETC deutlich höher als der von SC. Dies ist auf die Tatsache zurückzuführen, dass die optischen und thermischen Verluste in ETC im Vergleich zu SC sehr gering sind. Die Wärmeenergieverluste pro Zeiteinheit

(W) wurden auch in Bezug auf die optischen Verluste berechnet. Die Studie kam zu dem Schluss, dass beide Systeme effektiv für die Milchpasteurisierung eingesetzt werden können; das auf ETC basierende solare Milchpasteurisierungssystem erwies sich jedoch als effizienter, einfacher im Design, billiger, stabiler, kompakter und kostengünstiger und bietet eine hervorragende Möglichkeit für die dezentrale Milchverarbeitung.

Als natürliches flüssiges Lebensmittel ist Milch eine vollwertige Nahrung, die alle wichtigen Mineralien wie Eiweiß, Fett und Vitamine enthält. Durch unsachgemäße Behandlung und Lagerung nach dem Melken kommt es jedoch zu einer Verschwendung aufgrund von Mikroorganismen und Bakterienvermehrung. In den Entwicklungsländern verdirbt die Frischmilch aufgrund der hohen Temperaturen. Bei der Verwendung von PV-Solaranlagen war die Minimierung des Drehmoments der Kältemaschinen eine große Herausforderung für das reibungslose Funktionieren des Milchkühlsystems, insbesondere für die konventionellen (Hubkolben-) Kompressoren. Die VRF-Technologie (Variable Refrigerant Flow) löste nicht nur das Problem der Drehmomentbelastung, sondern verringerte auch die Größe des Spitzenleistungsbedarfs der PV-Anlage. Dieses System besteht aus einem Milchkühltank (200 l Fassungsvermögen), der mit einer Tonne Kühlaggregat gekoppelt ist, das durch PV-Paneele (2 kWp) betrieben wird, und nutzt die VRF-Technologie, um das System durch Minimierung der Drehmomentbelastung energieeffizienter zu machen. Die Experimente wurden mit verschiedenen Chargengrößen (50L, 100L, 150L und 200L) durchgeführt, um die Rohmilch von 30ºC auf 4ºC abzukühlen. Während der Optimierungsphase wurde festgestellt, dass die für den Betrieb der verschiedenen Kompressor typen (Hubkolbenkompressor, Rotationskompressor mit Kondensator und Rotationskompressor mit VRF) erforderliche Vergleichsleistung 1,8 kW, 1,2 kW bzw. 0,8 kW beträgt, während die Drehmomentbelastung mit 3,3 kW, 1,6 kW und Null kW angegeben wurde. Der experimentelle und der modellierte prognostizierte Stromverbrauch und die Abkühlzeit bei verschiedenen Chargengrößen zeigten gute Korrelationskoeffizienten (R2 = 0,99, P < 0,0001). Es wurde festgestellt, dass etwa eine Tonne Kühlaggregat ausreicht, um 200 Liter Milch in weniger als zwei Stunden auf 4ºC zu kühlen, wie es die WHO-Normen für die Verarbeitung von Milch in landwirtschaftlichen Betrieben vorschreiben.

Milchverfälschungen sind bei der Verarbeitung und in der gesamten Versorgungskette sehr häufig, insbesondere in den am wenigsten entwickelten Ländern (LDC) wie Pakistan. Die Milchbauern müssen Rohmilch verkaufen, weil es keine ausreichenden Milchverarbeitungsanlagen ab Hof gibt, was zu wirtschaftlichen und qualitativen Kompromissen für Erzeuger und Verbraucher führt. Die aktuelle Studie wurde durchgeführt, um die Milchqualität zu untersuchen, die mit einem selbst entwickelten solaren Milchkühler (SMC) und einem solaren Milchpasteur (SMP) in Verbindung mit einem evakuierten Solarröhrenkollektor verarbeitet wurde, und zwar im Vergleich zur bestehenden Milchwertschöpfungskette und zur technisch-wirtschaftlichen Machbarkeit dieser entwickelten Technologien. Die Qualitätsmerkmale wie Fett (5,4 %), fettfreie Feststoffe (9,1 %), Salze (0,7 %), Protein (3,9 %), Laktose (4,2 %), Gesamtfeststoffgehalt (14,5 %), pH-Wert (6,85), Dichte (1,031 kg/l) und Gefrierpunkt (-0,532 °C) der verarbeiteten Milch lagen innerhalb der standardisierten Bereiche. Die Ergebnisse der sensorischen Bewertung anhand einer 9-stufigen hedonischen Skala zeigten, dass die solar verarbeitete Milch in Bezug auf Geschmack, Farbe, Aroma und Frische insgesamt positiv bewertet wurde. Bei einer geschätzten Betriebsdauer von 10 Jahren liegen die Amortisationszeiten für SMC und SMP bei 1,3 bis 4,5 bzw. 1,1 bis 2,7 Jahren, abhängig von der alternativen Quelle für die entsprechende Energieerzeugung. Die Verarbeitungskosten pro Liter Milch, sowohl für die Kühlung als auch für die Pasteurisierung, wurden mit diesen solarbetriebenen Technologien auf 0,003 USD berechnet.

Appendix A:



Location of Sample Data Points in Faisalabad District
72°40'0"E
72°50'0"E
73°0'0"E
73°10'0"E
73°20'0"E
73°30'0"E
73°40'0"E
31°50'0"N
31°40'0"N
31°30'0"N
31°20'0"N
31°10'0"N
31°0'0"N
30°50'0"N
30°40'0"N
30°30'0"N
N
S
E
W
Legend
District Boundary
Sample Points
0
15
30
60 Km

Appendix B: Milk Consumer Problems and Feedback on Milk Distribution system in Faisalabad

Milk Consumer Problems and Feedback on Milk Distribution system in Faisalabad

Interview schedule

District	Tehsil	Union Council	Village
Faisalabad			

1. Name of Respondent __________________________________

2. Gender of Respondent
   1. Male ☐ 2. Female ☐

3. Age of the Respondent

   ____

4. Education level of the respondent

1	2	3	4	5	6	7
Illiterate	Primary	Secondary	Matric	Intermediate	B.A	Above

5. Marital status of the respondent

1	2	3	4
Married	Single	Divorced	Widowed

6. Family type of the Respondent

   1. Nuclear ☐ 2. Joint ☐ 3. Extended ☐

7. Total family members of the respondent??

   Total ________ Female __________ Male____________

8. House ownership type

   1. Owned ☐ 2. Rented ☐ 3. Any other ☐

9. Type of house

   1. Pakka ☐ 2. Katcha ☐ 3. Semi Pakka ☐

10.Occupation of the Respondent

1	2	3	4	5	6
Agriculture	Business	Govt. job	Private job	Labor	Any other specify

11. What is your daily milk consumption (liters)? ______________________________

12. What type of milk you use?

1. Conventional Dairy Milk ☐ 2. Pasteurized Milk ☐ 3. Tetra Pack ☐

4.Any other (specify) __________

13. If Conventional, Then How do you collect the milk from the dairy system?

1. Supplied by Milk man 2. Collection from dairy farm
3. Distributed by dairy farmer. 4. Any other (specify)

14. What is the quality of the milk you receive every day?

1. Excellent.☐ 2. Good ☐ 3. Satisfactory ☐ 4. Poor ☐

15. What is the physical appearance of the milk?

1. Very good 2. Average 3. Dirty 4. Other (Specify) _________

16. What are the major impurities in the milk after sieving? ____

17. What is the temperature of milk at the time of milk collection?

1. Very warm. 2. Warm 3. Normal/atmospheric temp. 4. Cold

18. What is the viscosity of the milk you feel in comparison to standard milk?

1. Very thick 2. Thick 3. Thin 4. Very thin

19. Up to what extent are you satisfied with the milk distribution system?

1. 100%. 2. 75-99% 3. 50-74% 4. 25-49% 5. < 25%

20. What is the standard of cleanness, quality of the milk transportation containers?

1. 100% 2. 75-99% 3. 50-74% 4. 25-49% 5. < 25%

21. What is means of transpiration of milk at your doorstep .

1.By foot 2. Bicycle 3. Motorbike 4. Any other ___________

22. Material of container in which milk is supplied to you

1. Stainless Steel 2.Plastic Drum 3.Iron container 4.Any other _________

23. Are you satisfied with the sealing quality of container.

1. Yes 2. NO

24. What is the average price of milk per liter for above-mentioned parameters?

____

25. At evening time, how do you store the milk?

1. Use refrigerator
2. Addition of ice in the vessels
3. Other method

26. To what extent are you satisfied from this milk storage method?

1. To some extent 2. To great extent 3. Not at all

27. For how much time, you can keep the Milk, Safe, with your Storage Method?

1	2	3	4	5
12 hours	24	36	48	> 48

28. How much milk is lost due to improper storage facilities?

1	2	3	4	5
10%	10-20%	20-40%	40-60%	>80%
Mention electricity problems,				

29. Maximum milk spoilage season of the year?

1	2	3	4	5
Winter (Nov-Feb.)	Spring (Feb-Apr)	Summer (May-Aug)	Autumn (Sep.-Oct.)	Any Other

30. What factors causing trouble in your storage method?

Sr. no	Factors	1 To some extend	2 To great extend	3 Not at all
1	Old traditional method of storage			
2	Non availability of proper storage facilities			
3	Electricity problems			
4	Cultural and financial barriers			
5	Lack of awareness about proper storage methods			
6	Any other (specify)			
7	None			

31.Is the quality of milk has any harmful effects on the health of family or kids

1.Very often 2.Often 3.Rare 4.Very rare

32.Have you ever tried to analyze the quality of milk at any lab

1.Yes 2.No

if yes what was the results

1.Excellent 2.Good 3.Normal 4.Poor

33. Do you want some Improvement in this milk storage method?

1. Yes 2. No 3. If yes (specify)

If Yes, What maximum cost you would afford for pasteurized milk per liter?

---

34. UAF (University of agriculture Faisalabad) is planning to develop a solar-based milk pasteurizer in collaboration with German Government (DAAD). Would you prefer to buy pasteurized milk?

1. Yes 2. No.

If Yes. Would you prefer to pay small amount of extra cost e.g. Rs. 5 per liter for best quality standardized pasteurized milk with certain shelf life.

1. Yes 2. No.

If. No. What are your preferences or suggestions? ____
____
____

35. Any other comments to improve milk quality and milk distribution system. ____
____

Thanks for your valued time.

Appendix C: Estimation of milk production, farm size and farmers problems in Faisalabad district

Estimation of milk production , farm size and farmers problems in Faisalabad district

Interview schedule

District	Tehsil	Union Council	Village
Faisalabad			

1. Name of Respondent ________________________________

2. Gender of Respondent
   1. Male ☐ 2. Female ☐

3. Age of the Respondent

   ____

4. Education level of the respondent

1	2	3	4	5	6	7
Illiterate	Primary	Secondary	Matric	Intermediate	B.A	Above

5. Marital status of the respondent

1	2	3	4
Married	Single	Divorced	Widowed

6. Family type of the Respondent

   1. Nuclear ☐ 2. Joint ☐ 3. Extended ☐

7. Total family members of the respondent??

   Total ________ Female __________ Male____________

8. House ownership type

   1. Owned ☐ 2. Rented ☐ 3. Any other ☐

9.Type of house

   1. Pakka ☐ 2. Katcha ☐ 3. Semi Pakka ☐

1

10.Total land holding (Acre)____________

11. Occupation of the Respondent

1	2	3	4	5	6
Agriculture	Business	Govt. job	Private job	Labor	Any other specify

12. Do you possess Cattle?

1. Yes ☐ 2. No ☐

12(a). Basic source of income for survival?

1. Dairy only ☐ 2. Dairy and agriculture ☐ 3. Other ☐

13. If yes then what is the number of Cattle and their Daily Milk Production in liters?

Cattle	No. of Cattle	Daily Milk Production (litres)
Buffalo		
Cow		
Goat		
Any Other(Specify)		
Total		

14. Do you adopt any measure to increase the Milk Production of Cattle?

1. Yes ☐ 2. No ☐

15. If yes, what measure you use?

____

____

____

16. Which quantity of the milk you sale out on daily basis? (in liters)

1	2	3	4	5
5-25	25-50	50-75	75-100	>100

17. At what price (Rs) you sell per liter of milk ?

1	2	3	4	5
50	50-70	70-80	80-90	>90

18. What is your monthly income (Rs) by cattle milk sale?

1	2	3	4	5
<5000	<10000	10000-20000	20000-50000	>50000

19. What is your monthly expenditure on cattle maintenance ?

1	2	3	4	5
<5000	<10000	10000-20000	20000-50000	>50000

20. What monthly cost you spend just for milk storage?

1	2	3	4	5
<5000	<10000	10000-20000	20000-50000	>50000

21. At evening time, how do you store the Milk?

1. Use refrigerator ☐
2. Addition of ice in the vessels ☐
3. Other Method ______________________

22. To what extent are you satisfied from this milk storage method?

1. To some extent ☐ 2. To great extent ☐ 3. Not at all ☐

23. For how much time, you can keep the Milk, safe, with your storage method?

1	2	3	4	5
12 hours	24	36	48	> 48

24. How much milk is lost due to improper storage facilities?

1	2	3	4	5
10%	10-20%	20-40%	40-60%	>80%

25. Maximum milk spoilage season of the year ?

1	2	3	4	5

Winter (Nov-Feb.)	Spring (Feb-Apr)	Summer (May-Aug)	Autumn (Sep-Oct.)	Any Other

26. What is the amount of milk spoiled in different seasons ?

1	2	3	4	5
Winter (Nov-Feb.) No. of liters:	Spring (Feb-Apr) No. of liters:	Summer (May-Aug) No. of liters:	Autumn (Sep.- Oct.) No. of liters:	Any Other Please Specify No. of liters:

27. What factors causing trouble in your storage method?

Sr. no	**Factors**	**1 To some extend**	**2 To great extend**	**3 Not at all**
1	Old traditional method of storage			
2	Non availability of proper storage facilities			
3	Electricity problems			
4	Cultural and financial barriers			
5	Lack of awareness about proper storage methods			
6	Any Other (specify)			
7	None			

28. Do you want some Improvement in this Milk Storage Method?

1. Yes ☐ 2. No ☐

29. If yes, What kind of Improvement do you want?

Improvement	To No Extent	To some extent	To great extent
Better Storage in minimum time			
Better storage in minimum cost			

4

30. Do you need milk processing facilities for milk pasteurization?

1. Yes ☐ 2. No. ☐

If Yes , What would you prefer?

Solar based milk pasteurizer	Electric driven milk pasteurizer	Fossil fuels driven milk pasteurizer	Any other please specify

31. What method do you prefer for milk storage?

Solar based milk chiller	Electric based chillers	Ice storage method	Any other please specify

32. To what extent do you prefer you above option in Q. 30 and 31?

1 Strongly recommended	2 Recommended	3 Agreed	4 Disagree	5 Strongly disagree

33. Describe your overall problems regarding milk storage and on farm processing?

____
____
____
____

34. Give some suggestions to reduce the problems regarding Milk Storage and Farm Processing?

____
____
____

Appendix D:

BUSINESS RECORDER

Lahore, Wednesday 9 November 2016, 8 Safar 1438

Agriculture sector

Promotion of solar-based energy, technologies to cut post harvest losses

RECORDER REPORT

FAISALABAD: The promotion of solar-based energy and technologies would not only help the country to overcome energy crisis but also boost the agriculture sector by narrowing down post harvest losses with technologies including solar dryers and solar milk pasteurizer.

This was stated by University of Agriculture Faisalabad Vice Chancellor Prof Dr Iqrar Ahmad Khan while chairing the inaugural session on Attentive Energy for Community Development arranged by Department of Energy Engineering, University of Agriculture Faisalabad.

Vice Chancellor Prof Dr Iqrar Ahmad Khan said that as many as 95 percent of milk remained unprocessed. If we promote pasteurized milk technology at village level, it will help provide address the issue.

He said that the University had developed milk chiller that will save the nutritive values of the milk. He also said that the country was producing a huge quantity of biomass and crop residue every year that must be converted into electricity as an alternative way.

Pakistan Agriculture Research Council's Engineering Division Director General Dr Munir Ahmad said that the country was producing dates million tones but only 20 percent are dried with the sun lights. He stressed upon the need to promote solar dryer.

Dean Faculty of Agri Engineering Dr Allah Buksh said that pasteurized milk could be preserved for the longer shelf life hence it is marketable. He said that farming community don't get the proper price for milk due to non-availability of processing facilities at the farm level.

He said that the country spend the 14 million US dollar yearly on the import of oil.

Dr Munir Ahmad said that the country was importing the oil worth Rs 14 billion dollar to cater its need. He said that country can generate 3million MW solar energy. Whereas, 5000 MW can be generated from biomass, MPA Najma Afzal also spoke.

THE EXPRESS TRIBUNE

Wednesday NOVEMBER 9, 2016

Technological reforms

'Solar energy need of the hour to counter energy crisis'

SHAMSUL ISLAM
FAISALABAD

The promotion of solar-based energy and technologies would not only help the country overcome the energy crisis but also boost the agriculture sector by narrowing post-harvest losses.

University of Agriculture Vice-Chancellor Prof Dr Iqrar Ahmad Khan said this while chairing the inaugural session on Attentive Energy for Community Development. The event was arranged by Department of Energy Engineering, University of Agriculture, Faisalabad.

He said, "At least 95% milk remains unprocessed in Pakistan. If we promote pasteurised milk technology at village level, it will help address the issue." He added the university had developed a milk chiller that will save nutritive values of the milk.

The VC maintained the country was producing huge quantity of biomass and field residue every year that must be converted into electricity as an alternative way.

Pakistan Agriculture Research Council's Engineering Division Director General Dr Munir Ahmad said the country was producing millions of tonnes of dates but only 20% were dried with sunlight. He stressed upon the need to promote solar dryer.

Faculty of Agriculture and Engineering Dean Dr Allah Buksh said pasteurised milk could be preserved for a longer period, while the farming community do not get proper price for milk due to non-availability of processing facilities at the farms.

MODERN TECHNOLOGY: UAF Vic-Chancellor Prof Dr Iqrar Ahmad inspects a solar-based chiller. PHOTO: EXPRESS

NEED TO PRESERVE
95%
milk remains unprocessed in the country

INTERNATIONAL THE NEWS

Wednesday, November 9, 2016

'Solar-based technology to help overcome power crisis'

From Our Correspondent

FAISALABAD: The promotion of solar-based energy and technology will not only help the country overcome power crisis but also boost agriculture sector by narrowing down post-harvest losses, said University of Agriculture Faisalabad VC Prof Dr Iqrar Ahmad Khan.

Addressing a seminar on attentive energy for community development organised by the UAF Department of Energy Engineering, he said 95pc of milk remained unprocessed. He said: "If we promote pasteurized milk technology at the village level, it will help address the issue." He said the university had developed milk chiller that would save nutritive values of milk. He said the country was producing a huge quantity of biomass and crop residue every year that must be converted into electricity as an alternative way. Pakistan Agriculture Research Council Engineering Division DG Dr Munir Ahmad said the country was producing millions of tons dates but only 20pc were dried through sunlight. He stressed the need to promote solar dryer. Dean Faculty of Agri Engineering Dr Allah Bakhsh said pasteurized milk could be preserved for longer shelf life. He said the farmers did not get proper price for milk due to unavailability of processing facilities at farm level. He said the country spent $14 million yearly on import of oil. Dr Munir Ahmad claimed that the country could generate 3 million MW solar energy and 5,000 MW biomass energy. MPA Najma Afzal also spoke on the occasion.

FAISALABAD: UAF VC Prof Dr Iqrar Ahmad and others inspect a solar-based chiller at the varsity. —The News photo